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Zingiber officinale as a phytogenic additive for laying japanese quails

[*Zingiber officinale* como aditivo fitogênico para codornas japonesas em postura]

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Abstract: The objective of this study was to evaluate the effects of increasing dietary levels of ginger powder (0, 0.5, 1.0, 1.5, and 2.0 %) on the productive performance, nutrient metabolization, egg quality, gastrointestinal tract and bone (tibia and femur) biometry, and blood and tissue biochemical profile of laying Japanese quails. A total of 150 female Japanese quails (*Coturnix coturnix japonica*), aged 40 to 52 weeks, were distributed in a completely randomized design with five treatments and six replicates of five birds each over an 84-day experimental period. Ginger supplementation improved feed conversion ratio, increased the apparent metabolization coefficient of ether extract, and influenced some egg quality traits, including egg weight, yolk color, and eggshell thickness. In addition, it modified biochemical parameters related to lipid and mineral metabolism and promoted changes in gastrointestinal tract biometry, without consistent effects on the birds' bone characteristics. Ginger powder has potential as a phytogenic feed additive for laying Japanese quails, contributing to improved feed efficiency, selected egg quality traits, and the modulation of biochemical parameters, without compromising egg production or bird viability.

Keywords: natural additive; quail production; productive performance; powdered ginger.

Resumo: Objetivou-se avaliar os efeitos da inclusão de níveis crescentes de gengibre em pó (0; 0,5; 1,0; 1,5 e 2,0 %) na dieta de codornas japonesas em postura sobre o desempenho produtivo, a metabolização dos nutrientes, a qualidade dos ovos, a biometria do trato gastrointestinal e dos ossos (tíbia e fêmur), além do perfil bioquímico sanguíneo e tecidual. Foram utilizadas 150 codornas fêmeas (*Coturnix coturnix japonica*), com idade entre 40 e 52 semanas, distribuídas em delineamento inteiramente casualizado, com cinco tratamentos e seis repetições de cinco aves, durante 84 dias experimentais. A suplementação com gengibre promoveu melhora na conversão alimentar, aumento da metabolização aparente do extrato etéreo, alterações em algumas características da qualidade dos ovos, incluindo peso, coloração da gema e espessura da casca, além de modificar parâmetros bioquímicos relacionados ao metabolismo lipídico e mineral. Também foram observadas alterações na biometria do trato gastrointestinal, sem efeitos consistentes sobre as características ósseas das aves. Conclui-se que o gengibre em pó apresenta potencial como aditivo fitogênico para codornas japonesas em postura, contribuindo para melhorias na eficiência alimentar, em algumas características da qualidade dos ovos e na modulação de parâmetros bioquímicos, sem comprometer a produção de ovos ou a viabilidade das aves.

Palavras-chave: aditivo natural; coturnicultura; desempenho produtivo; gengibre em pó.

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1. Introduction

In recent years, several countries have restricted or prohibited the use of antibiotics as growth promoters in animal nutrition due to the risks associated with the selection of resistant microorganisms and their impacts on public health. In this context, the search for natural additives capable of improving productive performance and intestinal health in poultry without compromising food safety has intensified. Among these alternatives, phytogenic feed additives, obtained from medicinal plants and their derivatives, have attracted increasing interest because they exhibit antioxidant, antimicrobial, anti-inflammatory, immunomodulatory, and digestive properties, which may contribute to greater productive efficiency and sustainability of poultry production systems [1].

Ginger (*Zingiber officinale*) contains several bioactive compounds, such as flavonoids, terpenoids, and phenolic acids, which are responsible for important pharmacological effects, including antioxidant, antimicrobial, anti-inflammatory, immunomodulatory, antihyperlipidemic, antihyperglycemic, antitumor, and cardioprotective activities [2]. Among the main biologically active components are gingerol, shogaol, gingerdiol, gingerdione, and zingiberene, compounds capable of modulating the intestinal microbiota, stimulating the digestive system, and influencing enzymatic activity and gastrointestinal pH [3]. In addition, ginger is a source of minerals such as iron, calcium, phosphorus, zinc, copper, chromium, and manganese, as well as vitamin C and antioxidant compounds, including total polyphenols (840 mg/100 g), tannins (1.51 g/100 g), and flavonoids (2.98 g/100 g), exhibiting high antioxidant activity [4].

Studies have demonstrated positive effects of ginger supplementation in poultry nutrition. The inclusion of 0.05 g/kg of ginger powder in the diet increased egg production, hatchability, reproductive performance, and economic efficiency in Japanese quails [1]. In laying hens, supplementation with 100 g/ton of ginger improved egg quality by increasing Haugh units and albumen height [5]. Gurbuz and Salih [6] observed an increase in egg production and a reduction in cholesterol content with the inclusion of 10, 20, and 30 g/kg of ginger in the diet. Furthermore, the addition of ginger essential oil at 300 µL/kg of feed increased eggshell weight and thickness in laying hens [7]. However, the available results are still inconsistent regarding the optimal inclusion levels and the physiological mechanisms involved, especially in laying Japanese quails.

Although there are studies evaluating the effect of ginger on isolated performance or egg quality variables, research investigating, in an integrated manner, its effects on productive performance, nutrient digestibility, egg quality, gastrointestinal tract biometry, bone characteristics, and biochemical metabolism in laying Japanese quails is still scarce. A comprehensive understanding of these responses is important to elucidate the possible mechanisms of action of ginger and to provide scientific support for its use as a phytogenic feed additive in Japanese quail production systems.

Therefore, it was hypothesized that increasing levels of ginger powder in the diet of laying Japanese quails would be able to improve feed efficiency, enhance nutrient digestibility, promote positive changes in egg quality, and modulate biochemical and morphophysiological parameters without compromising the skeletal integrity of the birds.

Thus, the objective of this study was to evaluate the effects of increasing dietary levels of ginger powder (0.0, 0.5, 1.0, 1.5, and 2.0 %) on productive performance, nutrient digestibility, egg quality, gastrointestinal tract and bone (tibia and femur) biometry, as well as on the blood biochemical profile and the biochemical characteristics of the liver and pancreas in laying Japanese quails.

2. Material e métodos

The experiment was conducted at the Poultry Sector of the Instituto Federal Goiano – Rio Verde Campus, Goiás, Brazil, and the laboratory analyses were carried out at the Animal Nutrition and Animal Biochemistry and Metabolism Laboratories of the same institution. The experimental protocol was approved by the Animal Ethics Committee (CEUA) under protocol Nº. 6008300419.

A total of 150 female Japanese quails (*Coturnix coturnix japonica*), aged between 40 and 52 weeks and in the third laying cycle, were used. The birds were evaluated at this stage because it corresponds to a period of stabilized production, allowing the assessment of the effects of supplementation on productive, digestive, and metabolic parameters with less influence from the initial laying phase. The birds were previously standardized according to body weight and housed in galvanized wire cages (38 × 40 × 23 cm), providing a stocking density of 304 cm²/bird, equipped with nipple drinkers, trough feeders, and excreta collection trays.

A lighting program consisting of 16 hours of natural and artificial light per day was adopted using 100-W fluorescent lamps. Water and feed were provided *ad libitum* throughout the experimental period. The experiment lasted a total of 84 days, divided into three productive cycles of 28 days each. Minimum and maximum temperatures, as well as the relative humidity inside the poultry house, were recorded twice daily (08 and 16 h) using a digital thermo-hygrometer positioned at the center of the poultry house at bird height.

A completely randomized design (CRD) was adopted, consisting of five treatments and six replicates, with five birds per experimental unit. The treatments consisted of corn- and soybean meal-based diets supplemented with increasing levels of ginger powder (0.0, 0.5, 1.0, 1.5, and 2.0 %).

2.1 Ginger preparation

Ginger (*Zingiber officinale*) was obtained from fresh rhizomes purchased from a rural property located in the municipality of Ouroana, Goiás, Brazil (18°7'54" S; 50°37'3" W). The rhizomes were sliced, distributed on aluminum trays, and dehydrated in a forced-air circulation oven at 40°C for 72 h. Subsequently, the material was ground in a knife mill until a fine powder was obtained and stored under freezing conditions (-18°C) until use.

The proximate composition of the ginger powder was determined according to the methodology described by Silva & Queiroz [8], presenting 8.33 % moisture, 9.33 % crude protein, 2.84 % ether extract, and 7.45 % crude fiber. The experimental diets were formulated according to the nutritional recommendations of Rostagno et al. [9], and their composition is presented in Table 1.

Table 1. Ingredient composition and calculated nutritional levels of corn- and soybean meal-based diets supplemented with increasing levels of ginger powder.

Ingredients	Dietary ginger powder inclusion levels				
	0.0 %	0.5 %	1.0 %	1.5 %	2.0 %
Corn 8.58 %	56.26	56.26	56.26	56.26	56.26
Soybean meal 46 %	26.90	26.90	26.90	26.90	26.90
Mineral premix	0.10	0.10	0.10	0.10	0.10
Vitamin premix	0.20	0.20	0.20	0.20	0.20
Limestone	8.00	8.00	8.00	8.00	8.00
Dicalcium phosphate	1.03	1.03	1.03	1.03	1.03
Soybean oil	4.09	4.09	4.09	4.09	4.09
DL-Methionine	0.40	0.40	0.40	0.40	0.40
L-Lysine	0.48	0.48	0.48	0.48	0.48
L-Threonine	0.12	0.12	0.12	0.12	0.12
Salt	0.40	0.40	0.40	0.40	0.40
Ginger powder	----	0.50	1.00	1.50	2.00
Inert filler	2.00	1.50	1.00	0.50	0.00
Total (kg)	100.00	100.00	100.00	100.00	100.00
Calculated nutritional levels					
Metabolizable energy (kcal/kg)	2.800	2.800	2.800	2.800	2.800
Crude protein (%)	20.00	20.00	20.00	20.00	20.00
Crude fiber (%)	4.38	4.38	4.38	4.38	4.38
Digestible lysine (%)	1.07	1.07	1.07	1.07	1.06
Digestible methionine (%)	0.65	0.65	0.65	0.65	0.46
Digestible methionine + cystine (%)	0.88	0.88	0.88	0.88	0.87
Digestible threonine (%)	0.66	0.66	0.66	0.66	0.65
Digestible tryptophan (%)	0.22	0.22	0.22	0.22	0.22
Calcium (%)	3.24	3.24	3.24	3.24	3.24
Available phosphorus (%)	0.33	0.33	0.33	0.33	0.33
Sodium (%)	0.17	0.17	0.17	0.17	0.17

Laying mineral premix[1], %/kg of diet: crude protein, 2.4347 %; ether extract, 0.1781 %; crude fiber, 0.1495 %; calcium, 9.5243 %; total phosphorus, 6.5935 %; available phosphorus, 11.3059 %; sodium, 5.9693 %; arginine, 0.0262 %; lysine, 0.0178 %; methionine, 2.8835%; methionine + cystine, 2.8971 %; cystine, 0.0136 %; tryptophan, 0.0052 %; glycine, 0.0234 %; histidine, 0.0189 %; isoleucine, 0.0200 %; leucine, 0.0778 %; phenylalanine, 0.0305 %; tyrosine, 0.0212 %; threonine, 0.1696 %; valine, 0.0277 %; alanine, 0.0470%; releasable phosphorus, 0.0101%; phytase phosphorus, 4.7250%; efficiency, 468.7500; serine, 0.0306%; digestible phosphorus (poultry), 0.0082%; phytate phosphorus, 0.0126%; proline, 0.0833%; glutamic acid, 0.1198 %; electrolyte balance (NaAE), –0.8258 %; glycine + serine, 0.0540 %; potassium, 2.8675 %; chlorine, 5.0067 %; mineral matter, 71.6626 %; phenylalanine + tyrosine, 0.0517 %; metabolizable energy for breeders, 445 kcal/kg; metabolizable energy for poultry, 445 kcal/kg; linoleic acid, 0.0840 %; copper, 666.6666 ppm; iron, 1,666.2500 ppm; manganese, 3,830.6670 ppm; zinc, 3,333.7500 ppm; iodine, 66.7333 ppm; selenium, 13.2917 ppm; Ca:P ratio, 0.842 %; digestible arginine, 0.0234 %; digestible lysine, 0.0145 %; digestible methionine, 2.8824 %; digestible methionine + cystine, 2.8945 %; digestible cystine, 0.0116 %; digestible tryptophan, 0.0047 %; digestible threonine, 0.1660 %; digestible valine, 0.0243 %; digestible isoleucine, 0.0180 %. Laying vitamin premix[2]: vitamin A, 406.0000 IU/g; vitamin D_3, 171.0680 IU/g; vitamin E, 2,247.5000 ppm; vitamin K, 94.2238 ppm; vitamin B_1 (thiamine), 106.5866 ppm; vitamin B_2 (riboflavin), 417.6000 ppm; vitamin B_6 (pyridoxine), 181.2036 ppm; vitamin B_{12} (cyanocobalamin), 1.5370 ppm; folic acid, 133.3420 ppm; nicotinic acid, 1,348.5000 ppm; pantothenic acid, 681.5001 ppm; biotin, 9.7150 ppm; choline, 13,277.8500 ppm; antioxidant, 3,507.2500 ppm; tylosin, 1,837.0000 ppm; acid–base balance, 1,918.8490 mEq/kg; moisture, 1.9907 %.

2.2 Productive performance

At the beginning and end of each production cycle, birds and feed were weighed to determine productive performance parameters. Eggs were collected daily. The following parameters were evaluated: Feed intake – calculated as the difference between the amount of feed offered and the

feed refusals. Feed conversion per egg mass – calculated by dividing the total feed consumed by the weight of eggs produced and expressed as grams of feed per gram of egg (g/g). Feed conversion per dozen eggs – calculated by dividing the average feed intake by the number of dozens of eggs produced (g/dozen).

Laying rate and commercial viability – were calculated based on the eggs collected, recording the number of intact, broken, cracked, thin-shelled, shell-less, and deformed eggs twice daily to determine the laying percentage, with records entered into specific data sheets. Egg mass (g bird^{-1} day^{-1}) was calculated by multiplying the laying rate (%) by the average egg weight (g) and dividing the result by 100, according to the following equation: EM = (LR × EW)/100.

2.3 Digestibility trial

Total excreta collection was performed between the 15th and 19th day of each experimental cycle, twice daily. Ferric oxide (Fe_2O_3) at 1 % was used as an external marker on the first and last days of collection, according to Silva & Queiroz [8]. Excreta and feed samples were stored frozen and subsequently analyzed to determine dry matter (DM), crude protein (CP), ether extract (EE), and crude fiber (CF). The excreta were pre-dried in a forced-air oven at 55 ± 5°C, ground in a Wiley mill, and analyzed according to the official methodologies described by Silva & Queiroz [8].

The apparent metabolization coefficients of nutrients were determined according to the total excreta collection methodology described by Matterson et al. [10]. Samples of the experimental diets and excreta were analyzed for dry matter (DM), crude protein (CP), ether extract (EE), and crude fiber (CF), following the methodology described by Silva & Queiroz [8]. Excreta dry matter was initially determined in a forced-air oven at 55 ± 5°C for 72 h, and the final dry matter content of both diets and excreta was subsequently determined in an oven at 105°C for 12 h. Nitrogen content was determined by the micro-Kjeldahl method, and crude protein values were obtained by multiplying the nitrogen content by a factor of 6.25. Ether extract was determined using the Goldfisch method with petroleum ether as the solvent, and crude fiber was determined after acid and alkaline digestion according to Silva & Queiroz [8]. The apparent metabolization coefficients of crude protein (AMCCP), ether extract (AMCEE), and crude fiber (AMCCF) were calculated using the following equation: AMC (%) = [(Nutrient intake − Nutrient excretion) / Nutrient intake] × 100 where nutrient intake (g) corresponded to the product of feed intake and the concentration of the respective nutrient in the diet, while nutrient excretion (g) was obtained by multiplying the amount of excreta produced by the concentration of the nutrient in the excreta.

2.4 Egg quality

During one week of each production cycle, two intact eggs per replicate (morning and afternoon) were collected to determine the following parameters: External quality. Egg weight – determined by weighing the eggs on a precision balance (0.01 g), and the average egg weight per replicate was calculated. Specific gravity – all intact eggs produced per replicate were evaluated for external quality by determining specific gravity (g/mL) using the saline flotation method. Specific gravity was measured using a petroleum densimeter with densities of 1.060, 1.065, 1.070, 1.075, 1.080, 1.085, 1.090, and 1.100 [11]. Haugh unit – calculated using the equation: HU = 100 × log (H − 1.7 × W^0.37 + 7.6). where H is the albumen height (mm) and W is the whole egg weight (g).

Internal quality: Yolk weight – eggs were randomly selected, broken, the yolks manually separated, and weighed on a precision balance (0.01 g). Albumen weight – obtained by subtracting the yolk and shell weights from the whole egg weight. Yolk and albumen height – measured using a digital caliper with a precision of 0.01 mm. Yolk and albumen diameter – measured using a digital

caliper with a precision of 0.01 mm. Yolk color – evaluated using the DSM® YolkFan™, in which yolk color was visually compared with the color scale by three evaluators, according to Galobart et al. [12]. Yolk percentage – calculated based on total egg weight and yolk weight. Yolk and albumen pH – measured using a digital pH meter [13]. Albumen percentage – determined by difference: 100 − (% yolk + % shell). Yolk and albumen index – obtained by dividing the height by the diameter of the yolk and albumen, respectively [14]. Shell weight – shells were dried in a forced-air oven at 105°C for 24 h and weighed again on a precision balance (0.01 g). Shell thickness – including the shell membranes, was determined as the average of three measurements taken at the two poles and the equatorial region of the egg using a digital caliper with a precision of 0.01 mm. Shell percentage – calculated based on total egg weight and shell weight.

2.5 Gastrointestinal tract biometry

At the end of the experiment (84 days), one bird per replicate, representative of the average body weight of the experimental unit, was euthanized by cervical dislocation. During necropsy, the organs composing the gastrointestinal tract (esophagus, crop, proventriculus, gizzard, liver, small intestine, pancreas, and large intestine) were removed, measured, and weighed as follows: gastrointestinal tract length from the insertion of the esophagus into the oropharynx to the junction of the large intestine with the cloaca; weight of the proventriculus plus gizzard (with residual contents); pancreas weight after separation from the duodenal loop; small intestine weight, corresponding to the portion extending from the end of the muscular stomach to the beginning of the ceca; large intestine weight, represented by the ceca, colon, and rectum; and liver weight, including the gallbladder. The values obtained were used to calculate the relative weight of each organ using the following equation: Relative organ weight = (organ weight / live body weight) × 100 [15].

2.6 Serum biochemical profile

One bird per replicate was used for blood collection after euthanasia. Blood samples were centrifuged at 6,000 rpm for 10 min to obtain serum [16]. Serum concentrations of calcium (Ca), phosphorus (P), total protein (TP), triglycerides (TG), cholesterol (CHOL), aspartate aminotransferase (AST), alanine aminotransferase (ALT), creatinine (CREA), and glucose (GLU) were determined using commercial kits.

2.7 Hepatic and pancreatic analyses

During necropsy, the liver and pancreas were removed, placed in properly identified containers, and immediately frozen to stop enzymatic activity. Tissue samples were homogenized (1 g of tissue in 9 mL of water) and then centrifuged at 8,000 rpm at 4°C for 10 min. All procedures were performed using an ice bath and distilled water to prevent enzymatic activity loss [16]. The supernatant was subsequently collected for triplicate determination of amylase (AMY) and total protein (TP) in the pancreas, and aspartate aminotransferase (AST), alanine aminotransferase (ALT), triglycerides (TG), and cholesterol (CHOL) in the liver using commercial kits.

2.8 Bone evaluation

To determine tibia and femur weight and diameter, at 84 days of age, after euthanasia of one bird per replicate per treatment, the right tibiae and femora were removed, identified, cleaned of adhering tissues, weighed on an analytical balance, and their diameters measured using a digital caliper (Jomarca). The Seedor Index (SI) was obtained by dividing bone weight (mg) by bone length (mm) [17].

2.9 Statistical analysis

Data were subjected to analysis of variance (ANOVA) in a completely randomized design using SISVAR software version 5.6 [18]. When a significant effect was detected by the F-test ($P < 0.05$), linear and quadratic regression models were fitted according to the dietary levels of ginger powder, and the model showing statistical significance ($P < 0.05$) and the highest coefficient of determination (R^2) was selected.

Additionally, treatments containing ginger were compared with the control treatment (0.0 % inclusion) using Dunnett's test at the 5 % significance level, performed with R software [19]. In the tables, means followed by different uppercase letters differ from the control treatment according to Dunnett's test ($P < 0.05$).

3. Results

During the experimental period, the average ambient temperature ranged from 24.9 to 28.9 °C, while the average relative humidity ranged from 43 to 51 %. The productive performance results of Japanese quails fed diets containing increasing levels of ginger powder are presented in Table 2. Ginger supplementation did not affect ($P > 0.05$) egg mass (EM), laying rate (LR), or bird viability (BV). In contrast, significant effects were observed for feed intake (FI), feed conversion ratio per egg mass (FCRM), and feed conversion ratio per dozen eggs (FCRD).

Feed intake differed from the control treatment at the dietary inclusion levels of 0.5, 1.5, and 2.0 % ginger powder and showed a quadratic response ($P < 0.05$), with the maximum response estimated at 0.85 % dietary inclusion. Feed conversion ratio per egg mass differed from the control treatment at the 1.5 % inclusion level and showed a quadratic response, with the lowest estimated value at 1.44 % dietary inclusion. Likewise, feed conversion ratio per dozen eggs differed from the control treatment at the 1.5 and 2.0 % inclusion levels, exhibiting a quadratic response with the lowest estimated value at 0.84 % dietary inclusion.

Table 2. Productive performance of Japanese quails fed corn- and soybean meal-based diets supplemented with increasing levels of ginger powder.

Variables	Dietary ginger powder inclusion levels (%)					P-value	SEM[1]	CV[2]
	0.0	0.5	1.0	1.5	2.0			
FI (g/bird/day)[3]	28.814A	29.148B	28.850A	28.283B	29.630B	0.0000	0.0377	0.26
FCRM (g/g)[4]	2.577A	2.558A	2.590A	2.442B	2.567A	0.0025	0.0229	1.80
FCRD (g/dozen)[5]	0.336A	0.340A	0.336A	0.330B	0.345B	0.0000	0.0004	0.28
EM (g/bird/day)	10.787	10.546	10.346	10.346	11.367	0.1584	0.3068	5.75
LR (%)	93.928	91.964	92.678	88.571	90.892	0.7687	3.0068	6.56
BV (%)	96.706	99.626	99.515	98.542	98.745	0.3264	1.0419	2.11

[1]Standard error of the mean (SEM). [2]Coefficient of variation (CV). Means followed by different uppercase letters within the same row differ from the control treatment according to Dunnett's test ($P < 0.05$). [3]Quadratic effect ($\hat{Y} = 0.5026x^2 - 0.8520x + 29.043$; $R^2 = 28.68$). Optimal level = 0.85 %. [4]Quadratic effect ($\hat{Y} = 0.0312x^2 - 0.0896x + 2.5899$; $R^2 = 18.74$). Optimal level = 1.44 %. [5]Quadratic effect ($\hat{Y} = 0.0057x^2 - 0.0096x + 0.3388$; $R^2 = 28.48$). Optimal level = 0.84 %. FI (g/bird/day): Feed intake; FCRM (g/g): Feed conversion ratio per egg mass; FCRD (g/dozen): Feed conversion ratio per dozen eggs; EM (g/bird/day): Egg mass; LR (%): Laying rate; BV (%): Bird viability.

The results for the apparent metabolization coefficients of nutrients in Japanese quails fed diets containing increasing levels of ginger powder are presented in Table 3. Ginger supplementation did not affect (P > 0.05) the apparent metabolization coefficients of crude protein (AMCCP) or crude fiber (AMCCF). However, a significant effect was observed for the apparent metabolization coefficient of ether extract (AMCEE), which differed from the control treatment at the dietary inclusion levels of 1.0 and 1.5 %. Regression analysis indicated a quadratic response (P < 0.05), with the maximum response estimated at 1.06 % dietary inclusion of ginger powder.

Table 3. Apparent metabolization coefficients of nutrients in Japanese quails fed corn- and soybean meal-based diets supplemented with increasing levels of ginger powder.

Variables	Dietary ginger powder inclusion levels (%)					P-value	SEM[1]	CV[2]
	0.0	0.5	1.0	1.5	2.0			
AMCCP (%)	88.319	87.833	87.746	89.032	87.776	0.5725	0.6343	1.44
AMCEE (%)[3]	89.019A	89.338A	91.214B	92.242B	88.349A	0.0004	0.5229	1.16
AMCCF (%)	86.348	83.451	84.545	84.276	83.763	0.1340	0.7831	1.85

[1]Standard error of the mean (SEM). [2]Coefficient of variation (CV). Means followed by different uppercase letters within the same row differ from the control treatment according to Dunnett's test (P < 0.05). [3]Quadratic effect ($\hat{Y}$ = -2,6489^2+5,6111x+88,3952, R^2 = 60,11). Optimal level = 1.06 %. AMCCP (%): Apparent metabolization coefficient of crude protein. AMCEE (%): Apparent metabolization coefficient of ether extract. AMCCF (%): Apparent metabolization coefficient of crude fiber.

The results for the egg quality of Japanese quails fed diets containing increasing levels of ginger powder are presented in Table 4. Ginger supplementation did not affect (P > 0.05) Haugh unit, specific gravity, yolk height, yolk percentage, or yolk pH, as well as albumen characteristics and shell weight and shell percentage.

However, significant effects were observed for egg weight, yolk diameter, yolk index, yolk color, and shell thickness. Egg weight differed from the control treatment at the 1.5 % dietary inclusion level and exhibited a quadratic response (P < 0.05), with the maximum response estimated at 1.35 % dietary inclusion. Yolk diameter differed from the control treatment at the 1.0 % inclusion level, whereas yolk index differed at the 0.5 and 1.5 % inclusion levels, showing a quadratic response. Yolk color differed from the control treatment at the 0.5 and 2.0 % dietary inclusion levels. For shell thickness, a significant difference was observed only at the 2.0 % dietary inclusion level of ginger powder.

Table 4. Egg quality of Japanese quails fed corn- and soybean meal-based diets supplemented with increasing levels of ginger powder.

Variables	Dietary ginger powder inclusion levels (%)					P-value	SEM[1]	CV[2]
	0.0	0.5	1.0	1.5	2.0			
Whole eggs								
Weight (g)[3]	11.300A	11.369A	11.242A	12.225B	11.304A	0.0009	0.1421	2.48
Haugh unit	87.763	89.449	88.455	90.683	89.683	0.3949	1.0807	2.42
SG (g/cm³)	1.073	1.072	1.069	1.069	1.069	0.3473	0.0016	0.31
Yolk								
Diameter (mm)	25.516A	24.742A	23.156B	25.461A	24.291A	0.0831	0.6092	4.95
Height (mm)	9.576	9.053	9.786	9.638	9.402	0.1385	0.1960	4.13
Index[4]	0.425A	0.371B	0.419A	0.377B	0.387A	0.0077	0.0109	5.50
Percentage (%)	31.27	31.90	31.20	31.32	31.63	0.8436	0.5055	3.21
pH	6.35	6.28	6.28	6.28	6.27	0.0826	0.0203	0.65
Yolk color[5]	3.62A	5.87B	4.12A	3.75A	4.62B	0.0000	0.2041	9.28
Albumen								
Diameter (mm)	38.143	35.653	37.303	37.932	35.878	0.2139	0.8996	4.87
Height (mm)	4.180	4.481	4.228	4.777	4.525	0.2167	0.1894	8.54
Index	0.145	0.126	0.118	0.123	0.126	0.6558	0.0129	20.32
Percentage (%)	60.44	59.49	60.08	60.85	60.01	0.6095	0.6111	2.03
pH	8.18	8.15	8.19	8.19	8.09	0.3674	0.0382	0.94
Shell								
Weight (g)	0.926	0.986	0.959	0.968	0.920	0.1729	0.0208	4.39
Percentage (%)	8.23	8.71	8.46	7.80	8.29	0.0890	0.2120	5.11
Thickness (mm)	0.440A	0.462A	0.453A	0.462A	0.481B	0.0570	0.0087	3.82

[1]Standard error of the mean (SEM). [2]Coefficient of variation (CV). Means followed by different uppercase letters within the same row differ from the control treatment according to Dunnett's test ($P < 0.05$). [3]Quadratic effect ($\hat{Y} = -0,2488x^2+0,6706x+11,1913$, $R^2 = 18,77$). Optimal level = 1.35 %. [4]Quadratic effect ($\hat{Y} = 0,0115x^2-0,0369x+0,4160$, $R^2 = 24,15$). Optimal level = 1,60 %. [5]Quadratic effect ($\hat{Y} = -0,3928x^2+0,7607x+4,2285$, $R^2 = 4,11$). Optimal level = 0,97 %. SG = Specific gravity (g/cm³). Yolk color (DSM YolkFan™).

The results for the gastrointestinal tract biometry of Japanese quails fed diets containing increasing levels of ginger powder are presented in Table 5. The results for the gastrointestinal tract biometry of Japanese quails fed diets containing increasing levels of ginger powder are presented in Table 5. No effects ($P > 0.05$) of ginger supplementation were observed on the relative weight of the gastrointestinal tract, proventriculus plus gizzard, large intestine, liver, or pancreas.

On the other hand, gastrointestinal tract length and the relative weight of the small intestine were affected by the treatments. Gastrointestinal tract length differed from the control treatment at the 1.0 % dietary inclusion level, exhibiting a quadratic response ($P < 0.05$), with the maximum response estimated at 1.07 % dietary inclusion. The relative weight of the small intestine differed from the control treatment at the 1.5 % inclusion level, also showing a quadratic response, with the maximum response estimated at 1.25 % dietary inclusion.

Table 5. Gastrointestinal tract biometry of Japanese quails fed corn- and soybean meal-based diets supplemented with increasing levels of ginger powder.

Variables	Dietary ginger powder inclusion levels (%)					P-value	SEM[1]	CV[2]
	0.0	0.5	1.0	1.5	2.0			
GITL (cm)[3]	39.855A	40.872A	45.873B	43.952A	39.711A	0.0087	1.2138	5.77
RGITW (g)	9.527	9.427	9.411	9.086	9.550	0.6045	0.2221	4.73
P+G (g)	2.486	2.441	2.546	2.553	2.437	0.7739	0.0827	6.64
RSIW (g)[4]	2.232A	2.367A	2.381A	2.599B	2.329A	0.0100	0.0608	5.11
RLIW (g)	0.877	0.887	1.050	1.004	0.973	0.1964	0.0569	11.88
RLW (g)	2.853	2.438	2.909	2.922	2.880	0.4388	0.2043	14.59
RPW (g)	0.278A	0.246A	0.256A	0.242A	0.234B	0.0629	0.0100	8.02

[1]Standard error of the mean (SEM). [2]Coefficient of variation (CV). Means followed by different uppercase letters within the same row differ from the control treatment according to Dunnett's test ($P < 0.05$). [3]Quadratic effect ($\hat{Y} = -4.9820x^2 + 10.6225x + 39.0034$; $R^2 = 75.23$). Optimal level = 1.07 %. [4]Quadratic effect ($\hat{Y} = -0.1731x^2 + 0.4316x + 2.2104$; $R^2 = 61.20$). Optimal level = 1.25 %. GITL (cm): Gastrointestinal tract length. RGITW (g): Relative gastrointestinal tract weight. P+G (g): Proventriculus + gizzard. RSIW (g): Relative small intestine weight. RLIW (g): Relative large intestine weight. RLW (g): Relative liver weight. RPW (g): Relative pancreas weight.

The results for the tibia and femur biometry of Japanese quails fed diets containing increasing levels of ginger powder are presented in Table 6. The results for the tibia and femur biometry of Japanese quails fed diets containing increasing levels of ginger powder are presented in Table 6. Ginger supplementation did not affect ($P > 0.05$) tibia weight, length, or Seedor Index, nor femur weight, width, or Seedor Index.

However, significant effects were observed for tibia width and for femur length and width. Tibia width differed from the control treatment at the 2.0 % dietary inclusion level, exhibiting a quadratic response ($P < 0.05$). For the femur, both length and width showed a quadratic response as a function of increasing dietary levels of ginger powder.

Table 6. Tibia and femur biometry of Japanese quails fed corn- and soybean meal-based diets supplemented with increasing levels of ginger powder.

Variables	Dietary ginger powder inclusion levels (%)					P-value	SEM[1]	CV[2]
	0.0	0.5	1.0	1.5	2.0			
Tibia								
Weight (g)	0.610	0.652	0.595	0.565	0.588	0.1800	0.0239	7.95
Length (mm)	47.897	48.542	48.395	48.105	48.307	0.8433	0.4299	1.78
Width (mm)[3]	2.822A	2.695A	2.818A	2.879A	2.711B	0.0224	0.0397	2.86
SI (mg/mm)	12.985	12.117	12.282	12.032	12.251	0.5978	0.4485	7.27
Femur								
Weight (g)	0.523	0.551	0.467	0.460	0.477	0.0650	0.0237	9.57
Length (mm)[4]	39.045	38.412	39.087	38.855	40.067	0.0495	0.3463	1.77
Width (mm)[5]	2.982	2.920	2.995	3.010	3.088	0.1278	0.0415	2.78
SI (mg/mm)	12.195	12.749	12.450	11.842	12.141	0.9244	0.7319	11.92

[1]Standard error of the mean (SEM). [2]Coefficient of variation (CV). Means followed by different uppercase letters within the same row differ from the control treatment according to Dunnett's test ($P < 0.05$). [3]Quadratic effect ($\hat{Y} = -0.0407x^2 + 0.0739x + 2.7724$; $R^2 = 6.40$). Optimal level = 0.91 %. [4]Quadratic effect ($\hat{Y} = 0.7950x^2 - 1.0925x + 38.9935$; $R^2 = 79.62$). Optimal level = 0.69 %. [5] Quadratic effect ($\hat{Y} = -0.04664x^2 + 0.1799x + 2.8740$; $R^2 = 89.64$). Optimal level = 1.92 %. SI (mg/mm): Seedor Index.

The results for the serum biochemical profile of Japanese quails fed diets containing increasing levels of ginger powder are presented in Table 7. Ginger supplementation promoted significant effects (P < 0.05) on the serum concentrations of calcium, phosphorus, Ca/P ratio, total protein, cholesterol, triglycerides, creatinine, glucose, AST, and ALT.

Serum calcium concentrations differed from the control treatment at all dietary inclusion levels, whereas the Ca/P ratio differed only at the 1.0 % inclusion level. Total protein concentrations differed from the control treatment at the 1.5 % inclusion level. Serum cholesterol, triglyceride, and creatinine concentrations differed from the control treatment at all evaluated supplementation levels. For glucose, a significant difference was observed only at the 2.0 % dietary inclusion level. Serum AST and ALT activities were also influenced by ginger supplementation, showing significant differences compared with the control treatment.

Table 7. Serum biochemical profile of Japanese quails fed corn- and soybean meal-based diets supplemented with 0.5, 1.0, 1.5, and 2.0 % ginger powder.

Variables	Dietary ginger powder inclusion levels (%)						SEM[1]	CV[2]
	0.0	0.5	1.0	1.5	2.0			
Ca (mg/dL)[3]	13.887A	14.740B	15.024B	15.324B	15.738B	0.0015	0.2348	3.14
P (mg/dL)[4]	5.236	4.706	4.470	5.174	6.363	0.0061	0.3104	11.96
Ca:P ratio[5]	2.608A	3.076A	3.286B	2.906A	2.542A	0.0191	0.1544	10.71
TP (g/dL)[6]	4.033A	4.452A	4.295A	5.958B	4.945A	0.0149	0.3618	15.28
CHOL (mg/dL)[7]	212.767A	106.244B	111.463B	108.946B	105.591B	0.0005	15.1749	23.53
TG (mg/dL)[8]	248.012A	159.448B	160.908B	131.467B	135.604B	0.0079	29.6902	24.77
CREA (mg/dL)[9]	0.540A	0.316B	0.341B	0.329B	0.316B	0.0000	0.0228	12.37
GLU (mg/dL)[10]	128.010A	133.012A	149.777A	140.376A	198.638B	0.0001	7.6789	10.24
AST (mg/dL)[11]	237.795A	227.681A	197.795B	221.431A	211.204A	0.0234	7.8022	7.12
ALT (mg/dL)[12]	50.062	64.125	47.041	39.854	33.500	0.0107	5.2812	22.51

[1]Standard error of the mean (SEM). [2]Coefficient of variation (CV). Means followed by different uppercase letters within the same row differ from the control treatment according to Dunnett's test (P < 0.05). [3]Quadratic effect ($\hat{Y} = -0.2458x^2 + 1.3480x + 13.9631$; $R^2 = 97.43$). Optimal level = 2.00 %. [4]Quadratic effect ($\hat{Y} = 1.2507x^2 - 1.9572x + 5.2714$; $R^2 = 99.01$). Optimal level = 0.78 %. [5]Quadratic effect ($\hat{Y} = -0.6444x^2 + 1.2287x + 2.6220$; $R^2 = 94.90$). Optimal level = 0.95 %. [6]Quadratic effect ($\hat{Y} = -0.2979x^2 + 1.2621x + 3.9220$; $R^2 = 51.45$). Optimal level = 2.00 %. [7]Quadratic effect ($\hat{Y} = 56.7434x^2 - 155.8168x + 199.7044$; $R^2 = 82.99$). Optimal level = 1.37 %. [8]Quadratic effect ($\hat{Y} = 44.1432x^2 - 138.8460x + 239.7196$; $R^2 = 90.91$). Optimal level = 1.57 %. [9]Quadratic effect ($\hat{Y} = 0.1099x^2 - 0.3068x + 0.5107$; $R^2 = 79.35$). Optimal level = 1.39 %. [10]Quadratic effect ($\hat{Y} = 22.9582x^2 - 16.1925x + 131.7180$; $R^2 = 82.65$). Optimal level = 0.35 %. [11]Quadratic effect ($\hat{Y} = 15.2272x^2 - 42.3409x + 238.6810$; $R^2 = 58.86$). Optimal level = 1.39 %. [12]Quadratic effect ($\hat{Y} = -8.8392x^2 + 6.1994x + 53.9761$; $R^2 = 74.23$). Optimal level = 0.35 %. Ca (mg/dL): Calcium; P (mg/dL): Phosphorus; Ca:P ratio: Calcium-to-phosphorus ratio; TP (g/dL): Total protein; CHOL (mg/dL): Cholesterol; TG (mg/dL): Triglycerides; CREA (mg/dL): Creatinine; GLU (mg/dL): Glucose; AST (U/L): Aspartate aminotransferase; ALT (U/L): Alanine aminotransferase.

The results for the biochemical profile of the liver and pancreatic tissues of Japanese quails fed diets containing increasing levels of ginger powder are presented in Table 8. In the liver tissue, no differences (P > 0.05) were observed for cholesterol, AST, or ALT. However, triglyceride levels differed from the control treatment at the 1.5 and 2.0 % dietary inclusion levels of ginger powder.

In the pancreatic tissue, ginger supplementation did not affect (P > 0.05) total protein concentrations. On the other hand, amylase activity differed from the control treatment at the 1.5 and 2.0 % dietary inclusion levels, showing a quadratic response (P < 0.05).

Table 8. Biochemical profile of liver and pancreatic tissues of Japanese quails fed corn- and soybean meal-based diets supplemented with 0.5, 1.0, 1.5, and 2.0 % ginger powder.

Variables	Dietary ginger powder inclusion levels (%)					SEM[1]	CV[2]
	0.0	0.5	1.0	1.5	2.0		
Liver							
CHOL (mg/dL)	244.585	256.900	273.885	219.957	271.337	0.7785	33.3194	26.30
TG (mg/dL)[3]	331.714A	360.8497A	291.451A	202.731B	251.593B	0.0005	18.6681	13.15
AST (mg/dL)	408.221	265.828	270.484	243.130	286.344	0.1821	48.6913	33.03
ALT (mg/dL)	85.093	82.437	85.093	86.031	91.890	0.5318	3.8619	8.97
Pancreas							
TP (g/dL)	1.221	1.537	1.784	1.354	1.339	0.4856	0.2310	31.92
AMY (mg/dL)[4]	439.756A	366.734A	356.997A	350.507B	314.807B	0.0158	21.9956	12.03

[1]Standard error of the mean (SEM). [2]Coefficient of variation (CV). Means followed by different uppercase letters within the same row differ from the control treatment according to Dunnett's test ($P < 0.05$). [3]Linear effect ($\hat{Y} = -63.6722x + 351.3404$; $R^2 = 64.04$). Optimal level = 2.00 %. [4]Quadratic effect ($\hat{Y} = 22.2544x^2 - 97.7339x + 430.1130$; $R^2 = 89.66$). Optimal level = 2.00 %. CHOL (mg/dL): Cholesterol; TG (mg/dL): Triglycerides; AST (U/L): Aspartate aminotransferase; ALT (U/L): Alanine aminotransferase; TP (g/dL): Total protein; AMY (U/L): Amylase.

4. Discussion

The environmental temperature recorded during the experimental period remained within the thermoneutral zone for adult quails, estimated between 18 and 28 °C, as described by Oide et al. [20]. The maximum (28.9 °C) and minimum (24.9 °C) temperatures, together with relative humidity ranging from 43 to 51 %, indicate that the birds were maintained under thermal comfort conditions, allowing the adequate expression of their productive potential and minimizing environmental interference with the evaluated variables.

Ginger powder supplementation promoted changes in variables related to feed efficiency and digestive physiology in Japanese quails, as evidenced by the improvement in feed conversion ratio, the increase in the apparent metabolization coefficient of ether extract, and modifications in gastrointestinal tract biometry. In contrast, egg mass, laying rate, and bird viability were not affected by the treatments, indicating that supplementation primarily influenced variables associated with feed efficiency and digestive physiology without affecting the main production indicators.

The observed effects may be related to the physiological properties of the main bioactive compounds present in ginger, especially gingerols, shogaols, and zingerone [2,21]. These compounds exhibit antioxidant and anti-inflammatory activities, in addition to acting on the digestive system by stimulating the secretion of digestive enzymes and bile, thereby enhancing nutrient digestion and absorption, particularly of lipids. Furthermore, studies have shown that phytogenic feed additives can positively modulate the intestinal microbiota, contributing to the maintenance of intestinal mucosal integrity and improving nutrient utilization efficiency [3, 22-29].

In the present study, this physiological response appears to be supported by the increase in the apparent metabolization coefficient of ether extract, associated with the greater length of the gastrointestinal tract and the higher relative weight of the small intestine. Although these variables were evaluated individually, their combined interpretation suggests morphofunctional adaptations capable of enhancing the utilization of the lipid fraction of the diet. Greater intestinal development may represent an increase in the absorptive surface available for nutrient digestion and absorption, thereby contributing to the improved feed efficiency observed in the supplemented birds [21, 30, 31].

Although an increase in feed intake was observed at some dietary inclusion levels, this result should not be interpreted as a direct consequence of improved nutrient digestibility. In poultry, greater digestive efficiency is not always associated with increased feed intake and may even result in maintenance or reduction of feed consumption due to improved dietary energy utilization [22, 32, 33]. Therefore, it is plausible to assume that the increase in feed intake observed in the present study was related to other physiological mechanisms, such as changes in diet palatability, stimulation of gastrointestinal motility, or modifications in digestive dynamics promoted by the bioactive compounds present in ginger. However, these mechanisms were not evaluated in the present study and, therefore, this hypothesis should be interpreted with caution.

The results obtained are partially consistent with studies conducted in Japanese quails and laying hens, in which ginger supplementation improved feed efficiency and some productive parameters, although the effects on feed intake and egg production vary among studies. These differences are probably related to the form of ginger processing (powder, extract, or essential oil), the concentration of bioactive compounds, the dietary inclusion level, the age of the birds, and the rearing conditions, all of which directly influence the physiological response to phytogenic feed additives [1, 5, 6, 26, 34-37].

Although ginger powder supplementation did not affect most internal and external egg quality characteristics, significant responses were observed for egg weight, yolk color, and eggshell thickness. These results indicate that the effects of the additive occurred specifically on certain attributes related to egg formation and composition, without compromising overall egg quality.

The increase in egg weight may be related to the improved utilization of nutrients promoted by ginger supplementation. Greater efficiency in the digestion and absorption of nutrients, especially lipids, amino acids, and minerals, may favor the deposition of structural egg components during egg formation. In addition, the phenolic compounds present in ginger exhibit high antioxidant capacity, reducing cellular oxidative stress and possibly contributing to the maintenance of the metabolic activity of tissues involved in the synthesis of egg constituents [1, 4, 5, 26, 38 - 42].

The greater yolk color intensity observed at some supplementation levels may be associated with the high concentration of phenolic compounds and natural pigments, such as 6-dehydrogingerdione, capable of intensifying the yellow coloration present in ginger, as well as with the possible increase in intestinal absorptive efficiency promoted by phytogenic feed additives. Although ginger is not considered an important source of carotenoids, its antioxidant activity may contribute to greater stability and deposition of fat-soluble pigments derived from the diet into the egg yolk [2, 12, 38, 43, 44].

The improvement observed in eggshell thickness may be related to the greater intestinal utilization of minerals involved in eggshell mineralization, mainly calcium and phosphorus [45, 46]. Although the present study did not demonstrate consistent changes in bone parameters, the modulation of mineral metabolism observed in the biochemical profile suggests that ginger supplementation may have increased the availability of these minerals for eggshell formation without causing significant structural changes in the bone tissue of the birds.

The results obtained partially corroborate studies conducted with Japanese quails and laying hens that demonstrated improvements in some egg quality characteristics following ginger supplementation. However, as observed in the present study, the effects do not always occur for all evaluated variables, indicating that the response depends on the form of ginger processing, the concentration of bioactive compounds, the dietary inclusion level, and the physiological characteristics of the birds [6, 5, 26, 36, 37, 47].

The results obtained in the present study demonstrated that ginger supplementation reduced serum cholesterol and triglyceride concentrations, in addition to decreasing hepatic triglyceride levels. Simultaneously, changes were observed in the serum activities of aminotransferases (AST and ALT), indicating that ginger exerted effects not only on systemic lipid metabolism but also on metabolic processes related to liver physiology. Taken together, these findings indicate that supplementation influenced mechanisms involved in lipid synthesis, utilization, and deposition, without evidence of impaired liver function.

The observed effects may be attributed to the bioactive compounds present in ginger, mainly gingerols, shogaols, and other phenolic compounds, which are recognized for their antioxidant activity and their modulatory effects on lipid metabolism. These compounds have been described in the literature as capable of reducing oxidative stress and modulating pathways involved in lipid metabolism by regulating the expression of enzymes and metabolic pathways associated with lipogenesis and fatty acid oxidation. Recent reviews have demonstrated that plant extracts can modulate the expression of genes related to lipid metabolism, stimulate β-oxidation, reduce lipid synthesis, and act on regulatory pathways such as PPARα and AMPK, thereby contributing to lower fat deposition and reduced cholesterol and triglyceride concentrations in poultry [25, 27, 48, 49].

The simultaneous reduction in serum and hepatic triglycerides observed in the present study reinforces the hypothesis that ginger exerted a systemic effect on lipid metabolism rather than merely causing a localized change in blood circulation. The liver is the primary organ responsible for lipid synthesis, storage, and distribution in birds, and changes in hepatic lipogenesis are expected to be accompanied by alterations in serum cholesterol and triglyceride concentrations. Therefore, the results obtained suggest reduced lipid synthesis and/or increased lipid utilization, a hypothesis consistent with the hypolipidemic action attributed to the bioactive compounds present in ginger [6, 26, 25, 42, 50].

The results obtained corroborate those reported by Herve et al. [26], who observed a significant reduction in serum cholesterol concentrations, as well as decreased AST and ALT activities in Japanese quails supplemented with ginger essential oil, without impairing productive performance. Similarly, Kairalla et al. [51] reported reduced serum cholesterol and triglyceride concentrations in broilers fed diets containing ginger powder, attributing these effects to the presence of bioactive compounds capable of stimulating digestive enzymes, improving nutrient utilization, and enhancing lipid utilization by the organism [27, 34, 37, 38, 52, 53].

The changes observed in serum AST and ALT activities should be interpreted with caution. Although these enzymes are widely used as indicators of liver alterations, small variations in their activities do not necessarily indicate hepatocellular injury [6, 21, 25, 26, 40, 54]. Considering that the present study did not identify other indicators consistent with liver impairment, it is more plausible to interpret these responses as metabolic adaptations resulting from ginger supplementation, possibly related to the reorganization of lipid metabolism and increased hepatic metabolic activity. This interpretation is supported by the lower cholesterol and triglyceride concentrations observed, indicating a physiological response consistent with the hypolipidemic effect of ginger.

In addition to the changes observed in the lipid profile, ginger supplementation promoted modifications in serum total protein concentrations. Plasma proteins are synthesized predominantly in the liver and constitute important indicators of hepatic functional capacity and the nutritional status of birds. Therefore, changes in this parameter should be interpreted together with other biochemical markers, such as AST, ALT, cholesterol, and triglycerides [2, 47]. Similar results were reported by Shewita and Taha [55] and Ibtisham et al. [56], who observed increased total protein concentrations in birds supplemented with ginger, accompanied by improvements in the lipid

profile, suggesting that these changes may be related to the modulation of hepatic metabolic activity and the antioxidant action of the bioactive compounds present in ginger. However, as this parameter may be influenced by several physiological and nutritional factors, its interpretation should be performed in conjunction with the other biochemical indicators.

Taken together, the results demonstrate that the main metabolic effect of ginger in the present study was the modulation of lipid metabolism, characterized by reductions in serum and hepatic lipid concentrations, probably resulting from the integrated action of its phenolic compounds on antioxidant, digestive, and metabolic regulatory mechanisms. These findings reinforce the potential of ginger as a phytogenic feed additive capable of improving lipid metabolism in Japanese quails without evidence of adverse effects on liver function.

Among the parameters related to energy metabolism, an increase in serum glucose concentration was observed only at the highest dietary inclusion level of ginger (2.0 %), while creatinine also showed a significant difference compared with the control treatment. However, these responses were not accompanied by changes in productive performance, bird viability, or other biochemical indicators suggestive of physiological impairment. Therefore, the results indicate that ginger supplementation influenced some aspects of intermediate metabolism; however, these effects should be interpreted in conjunction with the other evaluated parameters.

The increase in serum glucose observed in the present study deserves attention, since the effects of ginger on carbohydrate metabolism in poultry remain inconsistent in the literature. According to the review by Abd El-Hack et al. [1], ginger contains bioactive compounds capable of modulating different metabolic pathways, including those related to energy metabolism, digestion, and antioxidant activity. However, the magnitude and direction of these responses depend on factors such as the dietary dose, the processing method of ginger, the species, the age, and the physiological condition of the birds, with no consistent effect on blood glucose concentrations being reported [13].

Partially corroborating the present findings, Ibtisham et al. [56] observed an increase in serum glucose concentration in laying hens supplemented with ginger powder under heat stress conditions, accompanied by reductions in serum cholesterol and triglyceride concentrations and improvements in the antioxidant status of the birds. These authors suggested that the glycemic response may represent a metabolic adaptation resulting from increased energy availability and the antioxidant action of the bioactive compounds present in ginger, rather than a deleterious effect on metabolism. In the present study, although the birds were maintained under different conditions, the simultaneous occurrence of increased glucose and reduced serum lipid concentrations reinforces the hypothesis that ginger may modulate different metabolic pathways in an integrated manner.

On the other hand, the available literature is not consistent. In a recent study with ISA Brown laying hens, Zinalabidin et al. [57] reported that different sources and dietary inclusion levels of ginger did not promote significant changes in serum glucose, cholesterol, or total protein concentrations, although reductions in triglyceride levels were observed in some treatments. These discrepancies indicate that the metabolic response to ginger may vary according to the source of the raw material, the profile of bioactive compounds, the dietary inclusion level, the species, and the experimental conditions adopted, reinforcing the need for caution when interpreting these parameters [28, 29, 58, 59].

Creatinine is a metabolite derived from muscle metabolism, and its serum concentration is used as an indirect indicator of renal function and protein metabolism. Although differences among treatments were observed, these changes were not accompanied by evidence of clinical

impairment or by alterations in other biochemical parameters consistent with renal dysfunction. Therefore, this response is likely to represent a physiological adaptation resulting from ginger supplementation and should be interpreted together with the other findings related to energy metabolism [26, 44].

Taken together, the results suggest that ginger supplementation exerted a modest influence on the energy metabolism of Japanese quails, mainly evidenced by the alteration in serum glucose concentration. However, considering the absence of adverse effects on productive performance and the inconsistency of the available literature, it is not possible to conclude that ginger exerts a direct effect on glycemic homeostasis in birds. Therefore, additional studies are needed to clarify the physiological mechanisms involved and to determine whether these changes represent transient metabolic adaptations or dose- and management-dependent effects.

Ginger supplementation promoted changes in some parameters related to mineral metabolism, as evidenced by the modifications in serum calcium and phosphorus concentrations and in the Ca:P ratio. However, these biochemical changes were not accompanied by consistent alterations in bone biometry, since most of the variables evaluated in the tibia and femur did not differ significantly among the treatments. These results indicate that, under the conditions of the present study, the effects of ginger on mineral metabolism were not reflected in relevant structural changes in the bone tissue of Japanese quails.

Calcium and phosphorus play fundamental roles in bone mineralization and eggshell formation and are tightly regulated by hormonal and metabolic mechanisms that maintain mineral homeostasis in birds. Therefore, changes in the serum concentrations of these minerals do not always result in structural modifications of the bones, especially in short-term experiments or when dietary mineral levels meet the nutritional requirements of the birds. Thus, the biochemical changes observed may reflect physiological adjustments in mineral metabolism dynamics without necessarily indicating alterations in bone mineral deposition [45, 46, 52, 60].

Although no marked changes were observed in bone characteristics, the improvement in eggshell thickness observed at one of the supplementation levels suggests that part of the absorbed calcium may have been preferentially directed toward eggshell formation. In laying birds, a large proportion of the available calcium is mobilized to meet the high demand for eggshell calcification, which may explain the absence of structural responses in bone tissue despite the observed changes in mineral metabolism [13, 14, 45, 61].

The results obtained corroborate studies reporting that phytogenic feed additives may modify biochemical parameters related to mineral metabolism without promoting consistent changes in bone characteristics. These differences between biochemical and structural responses demonstrate that mineral metabolism is highly regulated and depends on several factors, including bird age, production stage, dietary mineral availability, and supplementation period [45, 46, 54].

Taken together, the results indicate that ginger supplementation promoted adjustments in the mineral metabolism of Japanese quails without evidence of consistent effects on bone structure. Therefore, the findings suggest that the main impact of supplementation was related to mineral homeostasis and eggshell formation, and it cannot be concluded that ginger exerts a direct effect on bone development under the conditions evaluated in the present study.

5. Conclusion

Ginger powder has potential as a phytogenic feed additive for laying Japanese quails, promoting improvements in feed conversion ratio, the apparent metabolization of ether extract, certain egg quality characteristics, and the modulation of biochemical parameters related to lipid and mineral metabolism, without compromising egg production or bird viability. Thus, ginger represents a promising alternative to conventional growth promoters in Japanese quail nutrition, although additional studies are needed to establish more consistent dietary inclusion levels and to confirm its effects under different rearing conditions.

Conflict of interest statement

The authors declare that they have no conflicts of interest.

Data availability statement

The complete dataset supporting the findings of this study is available within the published article.

Author contributions

Conceptualization: Sampaio, S. A.; Data curation: Morais, A. M. V. B.; Formal analysis: Sampaio, S. A. and Morais, L. V. B.; Methodology: Minafra, C. S. and Santos, F. R.; Supervision: Santos, F. R. and Minafra, C. S.; Visualization: Silva, J. M. S. and Soares, R. F.; Investigation: Morais, A. M. V. B. and Carvalho, A.; Writing (original draft): Morais, L. V. B. and Soares, R. F.; Writing (review and editing): Alvarenga, J. C. and Silva, J. M. S

Generative AI use statement

The authors did not use generative artificial intelligence tools or technologies in the preparation or editing of any part of this manuscript.

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