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The effect of cayenne pepper on meat yield and physicochemical composition of Ross 308 chicken meat

Vplyv kajenského korenia na mäsovú úžitkovosť a fyzikálno- chemické zloženie mäsa kurčiat Ross 308

Peter HAŠČÍK, Adam HANUSKA, Adriana PAVELKOVÁ (✉)

Slovak University of Agriculture in Nitra, Faculty of Biotechnology and Food Sciences, Institute of Food Sciences, Tr. A. Hlinku 2, 949 76 Nitra, Slovakia

✉ Corresponding author: adriana.pavelkova@uniag.sk

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ABSTRACT

This study evaluated the effects of dietary supplementation with cayenne pepper (*Capsicum frutescens* L.) on meat performance, chemical composition, amino acids and fatty acids profiles, and colour parameters of broiler chickens (Ross 308). A total of 500 birds were allocated into five groups (control and four experimental; n = 100/group). Experimental groups received cayenne pepper powder at inclusion levels of 0.1% (E1), 0.3% (E2), 0.5% (E3), and 0.7% (E4) for 42 days. Meat performance, chemical composition, amino acids and fatty acids profiles, and instrumental colour values (CIELAB) were determined. Carcass yield improved significantly in the highest inclusion group (E4), while live body weight and carcass weight were unaffected. Chemical analysis revealed that protein levels remained stable, whereas water content decreased and fat content slightly increased in breast muscle at higher inclusion levels. Cholesterol concentration in the thigh muscle decreased significantly already at the lowest supplementation (E1). Amino acids analysis demonstrated a dose-dependent effect: moderate supplementation maintained essential amino acids, whereas higher inclusion reduced threonine, valine, methionine, leucine, and lysine in both breast and thigh muscles. Fatty acids analysis revealed an increase in oleic acid, linoleic acid, and eicosapentaenoic acid in breast muscle, contributing to a higher proportion of MUFA but lower PUFA. Meat colour was also affected: breast lightness (L^*) and redness (a^*) values were significantly altered, while thigh muscle showed increased yellowness (b^*). These findings indicate that cayenne pepper supplementation can beneficially influence carcass yield, lipid profile, and meat colour, while its effects on amino acids are dose dependent.

Keywords: broiler chickens, cayenne pepper, meat, physical-chemical composition

ABSTRAKT

Táto štúdia hodnotila vplyv doplnkovej výživy kajenským korením (*Capsicum frutescens* L.) na mäsovú úžitkovosť, chemické zloženie, profily aminokyselín a mastných kyselín a farebné parametre mäsa brojlerových kurčiat Ross 308. Celkovo 500 kurčiat bolo rozdelených do piatich skupín (kontrolná a štyri experimentálne; n = 100/skupina). Experimentálne skupiny dostávali prášok z kajenského korenia v množstve 0,1 % (E1), 0,3 % (E2), 0,5 % (E3) a 0,7 % (E4) počas 42 dní. Stanovovala sa mäsová úžitkovosť, chemické zloženie, profily aminokyselín a mastných kyselín a inštrumentálne hodnoty farby (CIELAB). Výťažnosť jatočných tiel sa v skupine s najvyšším obsahom (E4) výrazne zlepšila, zatiaľ čo živá telesná hmotnosť a hmotnosť jatočného tela zostali nezmenené. Chemická analýza ukázala, že hladiny bielkovín zostali stabilné, zatiaľ čo obsah vody sa pri vyšších úrovniach pridávania kajenského korenia znížil a obsah tuku sa mierne zvýšil v prsnom svale. Koncentrácia cholesterolu v stehennom svale sa výrazne znížila už pri najnižšom dávkovaní (E1). Analýza aminokyselín preukázala účinok závislý od dávky: mierna suplementácia udržiavala esenciálne

aminokyseliny, zatiaľ čo vyššia suplementácia znížila hladinu treonínu, valínu, metionínu, leucínu a lyzínu v prsnom aj stehennom svale. Analýza mastných kyselín odhalila zvýšenie hladiny kyseliny olejovej, kyseliny linolovej a kyseliny eikozapentaénovej v prsnom svale, čo prispelo k vyššiemu podielu mononenasýtených mastných kyselín (MUFA), ale nižšiemu podielu polynenasýtených mastných kyselín (PUFA). Ovplyvnená bola aj farba mäsa: hodnoty svetlosti prs (L^*) a červenosti (a^*) sa významne zmenili, zatiaľ čo stehenný sval vykazoval zvýšenú žltosť (b^*). Tieto zistenia naznačujú, že suplementácia kajenským korením môže priaznivo ovplyvniť výťažnosť jatočných tiel, lipidový profil a farbu mäsa, zatiaľ čo jeho účinky na aminokyseliny sú závislé od dávky korenia.

Kľúčové slová: brojlerové kurčatá, kajenské korenie, mäso, fyzikálno-chemické zloženie

INTRODUCTION

Poultry meat is widely valued for its high-quality protein, low lipid content, and relatively high proportion of polyunsaturated fatty acids, making it an important contributor to a healthy human diet (Adegoke et al., 2023). Compared to other meats, chicken offers a favourable cholesterol profile and superior nutrient density in terms of protein and energy content (Marangoni et al., 2015). Consumer perception of poultry meat is strongly shaped by intrinsic attributes such as colour, fat content, and tenderness, as well as by extrinsic factors such as price and origin (Font-i-Furnols and Guerrero, 2014). Consequently, improving both the nutritional and sensory quality of broiler meat has become a key objective in poultry science.

Following the ban on antibiotic growth promoters, natural phytogenic additives have emerged as promising alternatives to enhance growth, feed efficiency, and product quality in broiler production (Munglang and Vidyarthi, 2020). Among these, peppers (*Capsicum* spp.) are of particular interest. They are rich in bioactive molecules such as capsaicinoids, carotenoids, flavonoids, vitamins, and essential fatty acids, which are linked with antioxidant, antimicrobial, and anti-inflammatory properties (Santos et al., 2023). Capsaicin, the principal pungent compound of cayenne pepper (*Capsicum frutescens* L.), has been reported to improve digestive enzyme activity, stimulate bile acid secretion, and reduce lipid peroxidation (Kentaro et al., 2002; Platel and Srinivasan, 2004). Such mechanisms may translate into improved nutrient utilization, growth performance, and meat quality.

Experimental studies have demonstrated that dietary inclusion of cayenne or hot red pepper enhances body weight gain, feed conversion efficiency, and carcass yield in broiler chickens (Al-Kassie et al., 2011; Atapattu and Belpagodagamage, 2011; El-Deek et al., 2012). Furthermore, supplementation with pepper powders has been shown to influence physico-chemical and technological properties of meat, including pH, water-holding capacity, cooking loss, and instrumental colour measurements (Adegoke et al., 2023). At the biochemical level, chilli peppers provide amino acids, polyunsaturated fatty acids such as linoleic and linolenic acid, and natural antioxidants like vitamin C, which are essential for maintaining oxidative stability and improving the nutritional profile of meat (Knazicka et al., 2025).

Nevertheless, findings remain inconsistent, as the magnitude and direction of effects depend on the level of pepper inclusion, the form of supplementation, and interactions with other dietary components (Adegoke et al., 2023). While low to moderate doses appear beneficial for growth and meat quality, higher levels may compromise sensory acceptability due to excessive pungency (Sanwo et al., 2020). Therefore, further research is needed to elucidate the impact of cayenne pepper on proximate composition (protein, fat, dry matter, cholesterol), amino acids and fatty acids profiles, colour, and carcass yield of broiler chickens.

This study aimed to investigate, evaluate and provide new insights into the potential of cayenne pepper as a functional feed additive in poultry nutrition that can improve meat performance and maintain the nutritional quality of the meat of broiler chickens.

MATERIAL AND METHODS

Slaughter and measurements

All experimental procedures were carried out in accordance with national animal protection legislation, and subsequently, the animals were slaughtered in accordance with European Union Regulation 1099/2009 on the protection of animals at the time of killing. In the experiment, 5 groups of Ross 308 broiler chickens (control and 4 experimental groups, n = 100 pcs/group) were created, where the control group was fed with standard feed without supplements and in the experimental groups (E1 - E4) cayenne pepper was added to the complete feed mixture at a dose of 0.1% (E1), 0.3% (E2), 0.5% (E3) and 0.7% (E4). From day 1 to day 42 of fattening, the fattening chickens had unlimited access to feed (feed mixture starter, grower) (Table 1) and drinking water, i.e. *ad libitum*. Subsequently, until the end of fattening (42 days), the chickens were fattened in such a way that their nutritional needs were ensured according to the recommended reference levels (Bulletin MARD SR, 2005).

Table 1. Composition of feed mixtures

Ingredients (%)	Starter (1^{st} – 21^{st} day of age)	Grower (22^{nd} – 42^{nd} day of age)
Wheat	42.00	40.00
Maize	22.50	30.00
Soybean meal (48% NS[1])	30.37	25.00
Calcium formate	1.00	1.20
Monocalcium phosphate	0.90	0.60
Fodder salt	0.38	0.38
Lysine	0.10	0.10
Methionine	0.15	0.12
Threonine	0.10	0.10
Soybean oil	2.00	2.00
Premix Euromix BR 0.5%[2]	0.50	0.50
Nutrient content (g/kg)		
Linoleic acid	21.93	23.19
Crude fibre	29.63	28.80
Crude protein	209.81	189.00
Ash	46.33	36.81
Ca	8.17	7.21
P	6.09	5.28
Na	1.79	1.78
ME_N ($MJ.kg^{-1}$)	11.63	11.89

[1] NS – nitrogen substances; [2] active substances per 1 kg of vitamin–mineral premix: vitamin A 2,500,000 IU; vitamin E 50,000 mg; vitamin D_3 800,000 IU; niacin 12,000 mg; pantothenic acid 3,000 mg; riboflavin 1,800 mg; pyridoxine 1,200 mg; thiamine 600 mg; menadione 800 mg; ascorbic acid 50,000 mg; folic acid 400 mg; biotin 40 mg; vitamin B_{12} 10 mg; choline 100,000 mg; betaine 50,000 mg; Mn 20,000 mg; Zn 16,000 mg; Fe 14,000 mg; Cu 2,400 mg; Co 80 mg; I 200 mg; Se 50 mg.

The feed mixture was prepared by Biofeed, Inc. (Kolárovo, the Slovak Republic). To determine the nutrient content and energy value of the feed mixture, an analysis was performed at the Institute of Nutrition and Genomics of the Faculty of Agrobiology and Food Resources of SUA in Nitra. The feed mixture was produced without the use of any antibiotics or coccidiostats. After 12 hours of starvation, each chicken was weighed on a KERN 440-49N scale with an accuracy of d = 0.01 g, and its live weight was determined. After determining the live weight, the chickens were selected and slaughtered in groups of 20 pieces based on the average live weight of the group without gender difference at the slaughterhouse of the Slovak University of Agriculture in Nitra. After necropsy, the carcasses were weighed to monitor the carcass weight (CW) and the weight of edible offal (gizzard, neck, heart, liver), or the monitored parts of meat performance, and subsequently, the corresponding slaughter yield was determined by calculation.

Chemical composition

The elemental chemical composition of the broiler chicken meat samples (water, crude protein, crude fat, and cholesterol content) was examined using the INFRATEC 1265 instrument (Germany), which uses transmittance mode to operate at intervals of 2 nm from 850 to 1050 nm. After being homogenized, the 50 g samples were put into a 90 × 90 × 15 mm glass cup and scanned twice. Each sample's spectrum was calculated as log 1/T (T = transmittance) and represented the average of five scan locations. The results are given in g/100 g. Every determination was made three times.

Amino acids composition

According to the methods employed by Straková et al. (2015), the Automatic Amino Acid Analyzer AAA 400 (Ingos a.s., Prague, Czech Republic) was used to determine the content of amino acids after acid hydrolysis in 6 N HCl at 110 °C for 24 hours. This was based on the colour-forming reaction of AA with the oxidative agent ninhydrin. After being recalculated to 100% dry matter, the resultant AA values were represented as grams of AA content per 100 g of muscle. There were two sets of determinations.

Fatty acids composition

Using Soxhlet extraction with petroleum ether, the total fat content was measured in accordance with ISO 12,966-2:2017: synthesis of methyl esters of fatty acids, animal and vegetable fats, and oils. According to Bobková et al. (2022), the individual profile was analysed using gas chromatography of fatty acids methyl esters. Three duplicates of the samples were used.

Meat colour measurement

Instrumental colour measurements of meat samples were performed using a spectrophotometer (Konica Minolta CM-2600d, Osaka, Japan) with the setting Specular Component Included (SCI). D65 light source and a 10° observer, with a port 8 mm in diameter, were used. The white plate calibration was performed at 23 °C, as suggested by the manual. The results were coordinates in the colour interface of the Commission Internationale de l'Eclairage (CIE) L^* a^* b^* system (L^*=0, black; L^*=100, white; 100 +a^*=redness; -a^*=greenness; +b^*=yellowness; -b^*=blueness). Using the optically passive glass aperture cover that came with the colorimeter to ensure a consistently level sample surface, colour measurements were made at three random positions on each sample (Bianchi, Fletcher and Smith, 2005). A white tile was used to calibrate the colorimeter (Minolta calibration plate: C: Y=93.66, =0.3150, y=0.3217).

Statistical analysis

All analyses were performed in triplicate, unless the description indicates otherwise. Results were reported as means ± standard deviations of measurements. Data were analyzed using Student's test at a significance level of $P \leq 0.05$ to test for differences between mean values. Data were analyses using XLSTAT® software (version 2018.5.52280, Addinsoft, New York).

RESULTS AND DISSCUSION

Meat performance

Key performance parameters (Table 2) showed moderate improvements with pepper supplementation, though not all differences were statistically significant. Live body weight and carcass weight did not differ significantly across groups (Live BW: C 2 095 ± 308 g → E4 2 221 ± 204 g, P = 0.478; Carcass weight: C 1 403 ± 221 g → E4 1 546 ± 163 g, P = 0.378). Carcass yield (%) was significantly higher in the highest inclusion group (E4: 75.67 ± 0.82%) compared with control (73.10 ± 2.96%; P = 0.043). Giblet weight and some cut weights (e.g. neck) were also higher in certain supplemented groups (giblets: C 124.48 ± 13.16 g → E4 146.55 ± 13.15 g; P = 0.037), and heart fat showed between-group differences (P = 0.037). Abdominal fat and thigh mass were not significantly affected.

The results of Adedoyin et al. (2019) and Munglang and Vidyarthi (2020) indicated that adding red pepper powder to broiler feed in different proportions led to an improvement in live weight. El-Tazi (2014) showed that broiler body weight and feed efficiency were significantly improved with hot red pepper in their diet at 0.5, 0.75, and 1% concentrations. The improvement in weight gain can be attributed to the fact that red pepper contains some ingredients with high nutritional value, such as the terpenoid compound capsaicin, capsanthin, capsicin, and vitamins.

Basic chemical composition of meat

Supplementation of broiler diets with cayenne pepper (*Capsicum frutescens*) significantly affected the overall composition of breast and thigh muscles, particularly water and cholesterol content (Table 3). In the breast muscle, water content decreased at the highest level of inclusion (E4: 69.02 ± 0.94 g/100 g) compared to the control group (71.74 ± 0.93 g/100 g; P < 0.0001). Protein levels remained unchanged within groups (24.6–25.4 g/100 g; P = 0.206), indicating that protein deposition in muscle was not affected by pepper supplementation. Fat content showed a slight increase in spice-fed groups, especially in E2 (0.66 ± 0.15 g/100 g; P = 0.032), while cholesterol concentration in breast muscle did not differ significantly between groups (P = 0.994). In the thigh muscle, water content was slightly lower in groups E3 and E4 (P = 0.029), while protein and fat remained stable. Cholesterol concentration decreased already at the lowest supplementation level (E1: 0.041 ± 0.007 g/100 g vs. control: 0.053 ± 0.005 g/100 g; P = 0.042). This suggests that even a small addition of cayenne pepper was sufficient to induce a hypocholesterolemic effect in thigh muscle, which may be related to higher metabolic activity and lipid turnover in dark muscle compared to white muscle. The present results are consistent with those of Adegoke et al. (2023), who reported that cayenne pepper powder did not alter crude protein content but affected water retention capacity. Similarly, Munglang and Vidyarthi (2020) summarized evidence showing that supplementation with hot red pepper can reduce blood cholesterol and triglyceride levels in broilers, thereby improving the lipid profile. In line with this, Dougnon et al. (2014) and Elamin et al. (2015) demonstrated that *C. frutescens* supplementation improved biochemical parameters and reduced cholesterol levels in broilers. The hypocholesterolemic effect observed in experiment is biologically well-substantiated. Capsaicin, the main pungent component of cayenne pepper, has been shown to increase bile acid secretion, inhibit lipid peroxidation, and act as a potent antioxidant (Kogure et al., 2002; Platel and Srinivasan, 2004). These mechanisms may reduce cholesterol accumulation in tissues and improve lipid metabolism. In addition, peppers are rich in carotenoids such as capsanthin, capsorubin, and β-carotene, which serve as natural antioxidants and may contribute to the stabilization of muscle lipids and pigments (Carvalho et al., 2006; Santos et al., 2023). In addition to carotenoids, *Capsicum frutescens* contain polyunsaturated fatty acids, especially linoleic and α-linolenic acids, as well as phenolic compounds (Rodrigues et al., 2021). These components are associated with hypolipidemic and antioxidant effects, which could partly explain the reduction in cholesterol in thigh muscles in this study.

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Table 2. Effect of cayenne pepper on meat performance parameters of broiler chickens Ross 308

Parameter	C	E1	E2	E3	E4	*P* Value
Live body weight (g)	2095.33 ± 307.85	2212.83 ± 218.44	2029.17 ± 112.40	2017.50 ± 249.16	2220.83 ± 203.89	0.478
Carcass weight (g)	1403.38 ± 221.17	1532.10 ± 154.00	1402.33 ± 76.43	1381.52 ± 171.81	1545.67 ± 163.40	0.378
Giblets weight (g)	124.48 ± 13.16^{b}	141.30 ± 18.05^{ab}	141.48 ± 11.00^{ab}	131.95 ± 13.37^{ab}	146.55 ± 13.15^{a}	0.037
Carcass yield (%)	73.10 ± 2.96^{b}	74.76 ± 1.78^{ab}	74.53 ± 1.28^{ab}	74.00 ± 1.31^{ab}	75.67 ± 0.82^{a}	0.043
Liver (g)	35.48 ± 1.52	43.57 ± 1.16	38.87 ± 1.40	35.77 ± 1.50	39.88 ± 1.54	0.200
Gizzard (g)	23.50 ± 6.12	21.70 ± 7.15	26.15 ± 4.06	25.40 ± 4.83	27.02 ± 5.34	0.223
Heart (g)	8.83 ± 0.44	9.77 ± 0.81	9.43 ± 0.72	8.10 ± 0.23	10.08 ± 0.25	0.225
Neck (g)	57.68 ± 4.75^{b}	62.58 ± 2.40^{ab}	71.23 ± 2.27^{ab}	64.08 ± 4.04^{ab}	72.40 ± 4.18^{a}	0.028
Breast (g)	286.67 ± 57.31	278.12 ± 68.85	259.95 ± 50.83	250.92 ± 59.03	303.82 ± 57.57	0.376
Thigh (g)	205.42 ± 11.81	223.58 ± 11.72	214.05 ± 7.14	215.58 ± 13.78	218.92 ± 12.72	0.884
Abdominal fat (g)	7.33 ± 1.51	11.13 ± 0.89	11.80 ± 0.94	12.78 ± 1.18	8.48 ± 0.66	0.177
Gizzard fat (g)	5.58 ± 2.46	4.80 ± 2.07	6.17 ± 3.86	5.60 ± 3.24	6.63 ± 3.39	0.831
Heart fat (g)	0.92 ± 0.05^{b}	0.67 ± 0.27^{b}	1.30 ± 0.29^{ab}	1.05 ± 0.25^{ab}	1.63 ± 0.27^{a}	0.037
Internal fats (g)	13.83 ± 0.61	16.60 ± 0.76	19.27 ± 0.34	19.43 ± 0.68	16.74 ± 0.50	0.267

Notes: C-control group, E1-E4 – experimental groups; Mean ± *SD* (standard deviation); Different superscript letters in rows (a, b) indicate statistically significant differences ($P \leq 0.05$).

Table 3. Basic chemical composition of breast and thigh muscle without and after application of cayenne pepper (g/100 g)

Group	Water	Protein	Fat	Cholesterol
		Breast muscle		
C	71.74 ± 0.93^{a}	24.58 ± 0.85^{a}	0.40 ± 0.12^{b}	0.036 ± 0.004^{a}
E1	70.82 ± 0.52^{ab}	24.77 ± 0.98^{a}	0.53 ± 0.27^{ab}	0.036 ± 0.004^{a}
E2	70.59 ± 0.39^{b}	25.39 ± 0.63^{a}	0.66 ± 0.15^{a}	0.035 ± 0.002^{a}
E3	70.79 ± 0.63^{ab}	24.62 ± 0.34^{a}	0.54 ± 0.20^{ab}	0.035 ± 0.006^{a}
E4	69.02 ± 0.94^{c}	25.29 ± 0.33^{a}	0.58 ± 0.08^{ab}	0.036 ± 0.005^{a}
P Value	<0.0001	0.206	0.032	0.994
		Thigh muscle		
C	70.78 ± 0.66^{ab}	22.92 ± 0.24^{a}	1.56 ± 0.41^{a}	0.053 ± 0.005^{a}
E1	71.04 ± 1.05^{a}	23.50 ± 0.66^{a}	1.11 ± 0.53^{a}	0.041 ± 0.007^{b}
E2	70.98 ± 0.78^{a}	23.34 ± 0.43^{a}	1.05 ± 0.38^{a}	0.042 ± 0.005^{ab}
E3	69.77 ± 1.01^{b}	22.93 ± 0.88^{a}	1.15 ± 0.69^{a}	0.044 ± 0.013^{ab}
E4	69.67 ± 0.60^{b}	23.20 ± 0.49^{a}	1.47 ± 0.26^{a}	0.047 ± 0.005^{ab}
P Value	0.029	0.455	0.346	0.042

Notes: C-control group, E1-E4 – experimental groups; Mean ± *SD* (standard deviation); Different superscript letters in column (a, b) indicate statistically significant differences ($P \leq 0.05$).

Similar results were reported by Al-Kassie et al. (2011), Atapattu and Belpagodagamage (2011), and El-Deek et al. (2012), who observed a reduction in lipid fractions and an improvement in growth and carcass traits in broiler-fed diets supplemented with hot red pepper. Overall, the current findings suggest that cayenne pepper supplementation does not compromise the protein content of broiler muscles but may favorably modulate lipid fractions, as evidenced by lower cholesterol in thigh muscles. These results are consistent with the literature highlighting the potential of chilli peppers as natural ingredients capable of improving the nutritional quality of poultry meat (Dougnon et al., 2014; Elamin et al., 2015; Munglang and Vidyarthi, 2020; Adegoke et al., 2023; Santos et al., 2023).

Amino acids composition

Dietary supplementation with cayenne pepper induced statistically significant, dose-dependent changes in the concentrations of several amino acids in both breast and thigh muscles. In general, moderate supplementation (E1 - E2) maintained or slightly increased some amino acids relative to control, whereas the higher inclusion levels (E3 - E4) were associated with reductions in multiple essential amino acids. Examples include threonine (breast: C 0.92 ± 0.13 → E3 0.62 ± 0.05 g/100 g, $P = 0.001$), valine (breast: C 0.86 ± 0.11 → E3 0.64 ± 0.04 g/100 g, $P = 0.002$), methionine (breast: C 0.58 ± 0.08 → E3 0.43 ± 0.02 g/100 g, $P = 0.003$), leucine (breast: C 1.57 ± 0.26 → E3 1.04 ± 0.09 g/100 g, $P = 0.001$) and lysine (breast: C 1.70 ± 0.30 → E3 1.11 ± 0.11 g/100 g, $P = 0.002$). Comparable patterns were observed in thigh muscle: for instance, threonine (thigh: C 0.78 ± 0.10 → E3 0.68 ± 0.06 g/100 g, $P = 0.026$) and leucine (thigh: C 1.32 ± 0.21 → E3 1.18 ± 0.13 g/100 g, $P = 0.028$). Some amino acids (e.g. cysteine, histidine, arginine) also showed significant between-group differences (Table 4).

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Table 4. Amino acid composition of chicken meat without and after application of cayenne pepper (g/100 g)

AA/Group	Part	C	E1	E2	E3	E4	*P* Value
Threonine	Thigh	0.78 ± 0.10^{a}	0.83 ± 0.05^{a}	0.80 ± 0.09^{a}	0.68 ± 0.06^{b}	0.73 ± 0.05^{ab}	0.026
	Breast	0.92 ± 0.13^{a}	0.80 ± 0.10^{ab}	0.79 ± 0.09^{b}	0.62 ± 0.05^{c}	0.69 ± 0.04^{bc}	0.001
Valine	Thigh	0.78 ± 0.08^{ab}	0.85 ± 0.04^{a}	0.81 ± 0.07^{a}	0.73 ± 0.05^{b}	0.77 ± 0.05^{ab}	0.042
	Breast	0.86 ± 0.11^{a}	0.77 ± 0.09^{ab}	0.77 ± 0.09^{ab}	0.64 ± 0.04^{c}	0.69 ± 0.03^{bc}	0.002
Methionine	Thigh	0.51 ±0.08^{b}	0.61 ± 0.05^{a}	0.54 ± 0.05^{ab}	0.48 ± 0.06^{b}	0.49 ± 0.06^{b}	0.017
	Breast	0.58 ± 0.08^{a}	0.54 ± 0.06^{ab}	0.52 ± 0.07^{ab}	0.43 ± 0.02^{c}	0.47 ± 0.04^{bc}	0.003
Isoleucine	Thigh	0.65 ± 0.12^{abc}	0.74 ± 0.05^{a}	0.69 ± 0.11^{ab}	0.57 ± 0.07^{c}	0.62 ± 0.05^{bc}	0.035
	Breast	0.79 ± 0.14^{a}	0.68 ± 0.13^{ab}	0.67 ± 0.11^{ab}	0.50 ± 0.05^{c}	0.56 ± 0.03^{bc}	0.001
Leucine	Thigh	1.32 ± 0.21^{abc}	1.50 ± 0.09^{a}	1.40 ± 0.19^{ab}	1.18 ± 0.13^{c}	1.26 ± 0.11^{bc}	0.028
	Breast	1.57 ± 0.26^{a}	1.38 ± 0.22^{ab}	1.35 ± 0.20^{ab}	1.04 ± 0.09^{c}	1.16 ± 0.07^{bc}	0.001
Phenylalanine	Thigh	0.68 ± 0.11^{ab}	0.78 ± 0.05^{a}	0.73 ± 0.09^{ab}	0.62 ± 0.07^{b}	0.66 ± 0.06^{b}	0.032
	Breast	0.81 ± 0.14^{a}	0.71 ± 0.11^{ab}	0.69 ± 0.11^{ab}	0.54 ± 0.05^{c}	0.60 ± 0.04^{bc}	0.002
Lysine	Thigh	1.40 ± 0.24^{ab}	1.61 ± 0.10^{a}	1.50 ± 0.22^{ab}	1.26 ± 0.14^{b}	1.35 ± 0.13^{b}	0.036
	Breast	1.70 ± 0.30^{a}	1.48 ± 0.26^{ab}	1.45 ± 0.24^{ab}	1.11 ± 0.11^{c}	1.23 ± 0.08^{bc}	0.002
Cysteine	Thigh	0.24 ± 0.03^{ab}	0.27 ± 0.02^{a}	0.24 ± 0.02^{ab}	0.22 ± 0.03^{b}	0.22 ± 0.02^{b}	0.021
	Breast	0.26 ± 0.03^{a}	0.25 ± 0.01^{ab}	0.23 ± 0.02^{ab}	0.20 ± 0.01^{c}	0.23 ± 0.02^{bc}	0.001
Histidine	Thigh	0.71 ± 0.11^{b}	0.86 ± 0.09^{a}	0.76 ± 0.08^{ab}	0.67 ± 0.11^{b}	0.70 ± 0.09^{b}	0.035
	Breast	0.78 ± 0.15^{a}	0.70 ± 0.11^{ab}	0.67 ± 0.11^{ab}	0.51 ± 0.04^{c}	0.58 ± 0.06^{bc}	0.003
Arginine	Thigh	1.05 ± 0.18^{ab}	1.20 ± 0.07^{a}	1.12 ± 0.17^{ab}	0.94 ± 0.10^{b}	1.01 ± 0.09^{b}	0.037
	Breast	1.28 ± 0.23^{a}	1.12 ± 0.20^{ab}	1.09 ± 0.18^{ab}	0.83 ± 0.08^{c}	0.92 ± 0.06^{bc}	0.002

Notes: C-control group, E1-E4 – experimental groups; Mean ± *SD* (standard deviation); Different superscript letters in rows (a, b) indicate statistically significant differences ($P \leq 0.05$).

The data indicate that low to moderate addition of cayenne pepper (E1–E2) tended to preserve or marginally enhance amino acid retention in muscle, while higher inclusion (E3 - E4) was associated with decreases in several essential amino acids. A plausible explanation is that bioactive compounds in *C. frutescens* (capsaicinoids, phenolics) at moderate doses may improve nutrient digestibility and metabolic efficiency (e.g. stimulation of digestive secretions and enzyme activity), supporting amino acids deposition (Platel and Srinivasan, 2004; Munglang and Vidyarthi, 2020). At higher doses, however, pungency or other physiological effects (e.g. transient reduced feed intake, altered gut motility, mild metabolic stress) could reduce net amino acid retention or shift protein turnover towards catabolism, leading to lower concentrations of some amino acids in muscle. Similar dose-dependent trends were reported in previous broiler studies with red pepper and related phytogenics (El-Deek et al., 2012; Dougnon et al., 2014; Elamin et al., 2015). Mechanistically, capsaicin modulates several pathways (digestive secretions, bile acid flow, thermogenesis) that can influence protein metabolism; excessive stimulation or stress may conversely limit anabolic deposition (Kogure et al., 2002; Platel and Srinivasan, 2004).

Fatty acids composition

Chicken dietary cayenne pepper altered the fatty acid profile of breast and — to a lesser extent — thigh muscle (Table 5). In breast muscle there was a significant increase in oleic acid (C18:1) at higher supplementation (breast oleic: C 22.05 ± 8.75 g/100 g → E3 35.77 ± 3.80; E4 37.80 ± 3.50; $P = 0.016$) and an increase in linoleic acid (C18:2) at some inclusion levels (breast linoleic: C 3.78 ± 0.94 → E1 5.22 ± 0.89; E4 5.27 ± 0.84; $P = 0.010$). EPA (eicosapentaenoic acid, C20:5) showed a progressive rise in breast muscle across inclusion levels (breast EPA: C 0.08 ± 0.02 → E4 0.13 ± 0.01; $P = 0.001$). In breast muscle total MUFA increased significantly in the higher inclusion groups in pepper (∑MUFA: C 47.10 ± 1.31 → E3/E4 ≈ 48.8 ± 0.9–1.2; $P = 0.027$), whereas total PUFA showed a modest but significant decrease overall in experimental groups compared with control (∑PUFA: C 13.40 ± 0.89 → E1–E4 ≈ 11.1–12.0; $P = 0.015$). In the thigh muscle, the changes were smaller and mostly non-significant for totals, although specific acids (e.g. vaccenic, linoleic, α-linolenic) displayed significant alterations across groups.

The observed enrichment of MUFA (especially oleic acid) and the changes in selected n-6 and n-3 fatty acids in breast muscle indicate that dietary pepper — or compounds associated with its oleoresin — can modulate muscle lipid composition. Potential mechanisms include altered lipid digestion/absorption (enhanced bile secretion and lipolytic activity mediated by capsaicin), modulation of hepatic lipid metabolism and desaturase/elongase activities, and antioxidant protection of unsaturated lipids preventing oxidative loss during deposition (Kogure et al., 2002; Platel and Srinivasan, 2004; Rodrigues et al., 2021; Santos et al., 2023). The increase in EPA in breast muscle is notable and may result from either improved retention of long-chain n-3 PUFA from the basal diet or altered metabolic conversion; similar findings (improved MUFA/PUFA balance) have been reported in pepper-supplementation studies (Adegoke et al., 2023). However, the decrease in total PUFA (breast) despite increased PUFAs highlights the complex effect of pepper supplementation on the full spectrum of fatty acids — likely reflecting interactions between fatty acids deposition, oxidation and tissue-specific lipid metabolism.

Meat Colour

The supplementation of broiler diets with cayenne pepper (*Capsicum frutescens*) influenced the colour characteristics of breast and thigh muscles (Table 6), as expressed in CIELAB parameters (L^*, a^*, b^*). In the thigh muscle, lightness (L^*) values ranged from 48.83 ± 1.62 (E1) to 51.28 ± 2.05 (E2), with no significant differences among treatments ($P = 0.249$). Redness (a^*) values were consistently negative, varying from −0.92 ± 0.11 (E1) to −0.15 ± 0.05 (E2), with no significant effect of supplementation ($P = 0.547$). Yellowness (b^*) values, however, were significantly affected ($P = 0.041$), with the highest value observed in group E2 (6.77 ± 0.79) compared with the control group (5.33 ± 2.07).

Table 5. Fatty acid composition of chicken meat without and after application of cayenne pepper (g/100 g)

FA/Group	Part	C	E1	E2	E3	E4	*P* Value
Lauric	Thigh	0.12 ± 0.01	0.12 ± 0.01	0.12 ± 0.01	0.12 ± 0.01	0.12 ± 0.01	0.433
	Breast	0.11 ± 0.01	0.12 ± 0.01	0.11 ± 0.01	0.12 ± 0.01	0.11 ± 0.01	0.080
Myristic	Thigh	1.38 ± 0.04	1.33 ± 0.02	1.38 ± 0.06	1.38 ± 0.03	1.38 ± 0.04	0.260
	Breast	1.43 ± 0.02^{a}	1.40 ± 0.04^{ab}	1.40 ± 0.04^{ab}	1.39 ± 0.05^{ab}	1.37 ± 0.03^{b}	0.024
Palmitic	Thigh	24.49 ± 0.28	24.35 ± 0.21	24.42 ± 0.23	24.48 ± 0.26	24.44 ± 0.17	0.868
	Breast	24.46 ± 0.18	24.38 ± 0.23	24.41 ± 0.32	24.38 ± 0.31	24.14 ± 0.12	0.291
Heptadecanoic	Thigh	0.34 ± 0.03	0.32 ± 0.02	0.31 ± 0.05	0.33 ± 0.04	0.32 ± 0.02	0.500
	Breast	0.27 ± 0.03^{b}	0.33 ± 0.06^{ab}	0.31 ± 0.07^{ab}	0.35 ± 0.05^{a}	0.34 ± 0.03^{ab}	0.038
Stearic	Thigh	10.66 ± 0.12	10.65 ± 0.27	10.46 ± 0.28	10.75 ± 0.25	10.61 ±0.33	0.489
	Breast	10.65 ± 0.16^{ab}	10.66 ± 0.20^{ab}	10.56 ± 0.18^{ab}	10.69 ± 0.23^{a}	10.38 ± 0.21^{b}	0.041
Oleic	Thigh	34.44 ± 7.03	37.31 ± 2.84	32.82 ± 7.90	38.74 ± 2.81	34.94 ± 2.34	0.404
	Breast	22.05 ± 8.75^{b}	31.02 ± 10.33^{ab}	29.08 ± 6.70^{ab}	35.77 ± 3.80a	37.80 ± 3.50^{a}	0.016
Vaccenic	Thigh	4.87 ± 0.13^{ab}	4.76 ± 0.13^{b}	4.94 ± 0.15^{a}	4.85 ± 0.11^{ab}	4.93 ± 0.11^{ab}	0.037
	Breast	4.98 ± 0.06	4.96 ± 0.11	4.98 ± 0.09	4.96 ± 0.10	4.99 ± 0.11	0.954
Linoleic	Thigh	4.33 ± 0.53^{ab}	5.12 ± 1.06^{a}	4.09 ± 0.84^{b}	4.63 ± 0.46^{ab}	4.27 ± 0.16^{ab}	0.035
	Breast	3.78 ± 0.94^{c}	5.22 ± 0.89^{ab}	4.22 ± 0.37^{ab}	5.06 ± 0.44^{ab}	5.27 ±0.84^{a}	0.010
Conjugated linoleic	Thigh	0.14 ± 0.02	0.14 ± 0.01	0.14 ± 0.01	0.14 ± 0.01	0.14 ± 0.01	0.915
	Breast	0.13 ± 0.02	0.14 ± 0.01	0.13 ± 0.01	0.14 ± 0.01	0.15 ± 0.01	0.169
α-Linolenic	Thigh	0.23 ± 0.02^{a}	0.17 ± 0.01^{cd}	0.20 ± 0.02^{ab}	0.16 ± 0.02^{d}	0.20 ± 0.01^{bc}	0.001
	Breast	0.25 ± 0.03^{a}	0.22 ± 0.03^{a}	0.23 ± 0.02^{a}	0.18 ± 0.03^{b}	0.21 ± 0.02^{a}	0.003
Eicosenoic	Thigh	0.64 ± 0.04^{a}	0.46 ± 0.10^{b}	0.59 ± 0.09^{a}	0.57 ± 0.09^{ab}	0.58 ± 0.10^{ab}	0.047
	Breast	0.69 ± 0.14	0.63 ± 0.12	0.74 ± 0.13	0.70 ± 0.07	0.73± 0.07	0.512

Continued. Table 5

FA/Group	Part	C	E1	E2	E3	E4	*P* Value
Arachidonic	Thigh	1.82 ± 0.28	1.77 ± 0.22	1.92 ± 0.27	1.82 ± 0.18	1.92 ± 0.21	0.791
	Breast	2.13 ± 0.18	1.97 ± 0.25	2.08 ± 0.27	2.05 ±0.36	2.02 ± 0.16	0.882
Eicosapentaenoic	Thigh	0.11 ±0.01	0.11 ± 0.02	0.10 ± 0.02	0.12 ± 0.01	0.12 ± 0.01	0.560
	Breast	0.08 ± 0.02^{c}	0.11 ± 0.02^{b}	0.10 ± 0.01^{bc}	0.12 ± 0.01^{ab}	0.13 ± 0.01^{a}	0.001
Docosapentaenoic	Thigh	0.14 ± 0.01	0.14 ± 0.01	0.14 ± 0.01	0.14 ± 0.01	0.14 ± 0.01	0.999
	Breast	0.13 ± 0.01	0.14 ± 0.02	0.12 ± 0.01	0.14 ± 0.01	0.14 ± 0.01	0.097
Docosahexaenoic	Thigh	0.04 ± 0.01	0.04 ± 0.01	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0.01	0.901
	Breast	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0.01	0.04 ± 0.01	0.616
Omega 3	Thigh	0.45 ± 0.04	0.48 ± 0.04	0.48 ± 0.06	0.44 ± 0.04	0.43 ± 0.05	0.360
	Breast	0.47 ± 0.05	0.47 ± 0.02	0.46 ± 0.06	0.43 ± 0.04	0.45 ± 0.05	0.595
Omega 6	Thigh	7.77 ± 0.42	8.08 ± 1.20	7.76 ± 0.48	7.42 ± 0.77	7.18 ± 0.31	0.344
	Breast	8.90 ± 0.46	8.29 ± 0.79	8.31 ± 0.33	8.26 ± 0.43	8.82 ± 0.70	0.218
∑ SAFA	Thigh	34.36 ± 1.40	34.98 ± 1.36	33.92 ± 2.34	34.83 ± 0.65	34.04 ± 1.21	0.743
	Breast	32.80 ± 0.79^{b}	33.91 ± 1.27^{ab}	33.11 ± 1.22^{ab}	34.26 ± 0.84^{a}	34.15 ± 0.79^{ab}	0.045
∑ MUFA	Thigh	49.11 ± 1.01	49.90 ± 1.06	48.15 ± 1.77	49.92 ± 1.80	48.88 ± 0.42	0.210
	Breast	47.10 ± 1.31^{b}	47.90 ± 1.14^{ab}	47.48 ± 1.16^{ab}	48.80 ± 0.89^{a}	48.81 ± 1.16^{a}	0.027
∑ PUFA	Thigh	10.11 ± 1.57	10.23 ± 0.94	10.44 ± 1.60	9.14 ± 1.00	9.69 ± 0.49	0.462
	Breast	13.40 ± 0.89^{a}	11.84 ± 1.71^{b}	12.02 ± 0.99^{ab}	11.10 ± 0.53^{b}	11.11 ± 0.80^{b}	0.015

Notes: C-control group, E1-E4 – experimental groups; Mean ± *SD* (standard deviation); Different superscript letters in rows (a, b,c, d) indicate statistically significant differences ($P \leq 0.05$).

In the breast muscle, significant differences were detected for both lightness (P = 0.023) and redness (P = 0.039). The highest L^* value was recorded in group E1 (46.50 ± 3.03), while the lowest was in E2 (42.12 ± 1.28). Redness values ranged from –2.08 ± 0.36 (E1) to –1.51 ± 0.31 (E4). Yellowness values did not differ significantly among treatments (P = 0.086). These findings indicate that breast meat colour was more responsive to dietary pepper inclusion than thigh meat, with noticeable changes in lightness and redness, while thigh meat was influenced mainly by yellowness.

Meat colour is an important indicator of poultry meat quality, influencing consumer choice and market value (Fletcher, 1999; Mancini and Hunt, 2005). The present results are consistent with earlier reports that dietary supplementation with cayenne pepper can modify muscle colour attributes. Adegoke et al. (2022) demonstrated that cayenne pepper powder improved broiler meat quality traits, including colour. The observed increase in thigh meat yellowness at moderate inclusion (E2) may be linked to the deposition of carotenoids such as capsanthin and β-carotene, abundant in red peppers (Carvalho et al., 2006; Rodrigues et al., 2021). Similarly, Santos et al. (2023) highlighted that carotenoids and phenolic compounds in *Capsicum frutescens* exert both pigmenting and antioxidant roles, contributing to enhanced muscle colour.

The effect of cayenne pepper on breast meat lightness and redness reflects the sensitivity of white muscle to oxidative changes. The reduction in lightness observed at E2, alongside slightly higher redness values in E3–E4, may indicate improved pigment stability mediated by antioxidant compounds. Capsaicin has been reported to inhibit lipid peroxidation and stabilize myoglobin, thereby preventing discoloration (Kogure et al., 2002; Platel and Srinivasan, 2004). Similar stabilizing effects of pepper-based additives on poultry meat pigments were noted by Atapattu and Belpagodagamage (2011) and El-Deek et al. (2012), who found that hot red pepper inclusion influenced meat colour depending on dosage.

Table 6. Evaluation of chicken meat color before and after application of cayenne pepper

Group/ Parameter	L^*	a^*	b^*
Thigh			
C	49.80 ± 2.45	-0.62 ± 0.19	5.33 ± 2.07^{ab}
E1	48.83 ± 1.62	-0.92 ± 0.11	4,32 ± 1.03^{b}
E2	51.28 ± 2.05	-0.15 ± 0.05	6.77 ± 0.79^{a}
E3	48.97 ± 3.04	-0.74 ± 0.26	5.33 ± 1.12^{ab}
E4	51.08 ± 0.88	-0.55 ± 0.06	5.87 ± 1.28^{ab}
P Value	0.249	0.547	0.041
Breast			
C	44.47 ± 1.10^{ab}	-1.76 ± 0.37^{ab}	3.64 ± 0.51
E1	46.50 ± 3.03^{a}	-2.08 ± 0.36^{a}	3.76 ± 0.80
E2	42.12 ± 1.28^{b}	-1.55 ± 0.25^{b}	3.40 ± 0.64
E3	44.37 ± 1.76^{ab}	-1.69 ± 0.37^{ab}	3.45 ± 0.48
E4	45.39 ± 1.97^{a}	-1.51 ± 0.31^{b}	3.71 ± 0.66
P Value	0.023	0.039	0.086

Notes: C-control group, E1-E4 – experimental groups; Mean ± *SD* (standard deviation); Different superscript letters in column (a, b) indicate statistically significant differences ($P \leq 0.05$).

The dose-dependent nature of the response observed in this study corresponds with findings of Munglang and Vidyarthi (2020), who reviewed that moderate levels of pepper supplementation tend to improve meat quality traits, whereas excessive amounts may reduce consumer acceptance due to pungency or colour imbalance. The current data confirm that moderate inclusion levels (E2) are sufficient to improve thigh meat yellowness, while higher levels did not yield further benefits.

Overall, the results demonstrate that dietary cayenne pepper supplementation can beneficially influence meat colour, with stronger effects on breast meat lightness and redness, and on thigh meat yellowness. These changes are likely related to the combined effects of carotenoids and capsaicinoids, which act as antioxidants and pigment stabilizers. The improvement of visual quality traits emphasizes the potential of *Capsicum frutescens* as a natural

feed additive to enhance the consumer appeal of poultry meat while maintaining its nutritional and technological quality, as previously suggested by Adegoke et al. (2022) and Santos et al. (2023).

Taken together, the results indicate that cayenne pepper exerts multifaceted effects on broiler meat composition and carcass utilisation that are dose dependent. At moderate inclusions (E1–E2), the additive supports maintenance of essential amino acids and can favourably modulate specific unsaturated fatty acids (e.g. linoleic, EPA). At higher inclusions (E3–E4), there is a trade-off: while MUFA (oleic) and some beneficial indices increase and carcass yield improves, several essential amino acids in muscle decline. Mechanistically, these patterns are consistent with the dual actions of *C. frutescens* constituents: (i) capsaicinoids and phenolics act as digestive stimulants and antioxidants, improving nutrient bioavailability and protecting unsaturated lipids from oxidation (Kogure et al., 2002; Platel and Srinivasan, 2004; Rodrigues et al., 2021; Santos et al., 2023), (ii) enhanced bile secretion and lipolysis facilitate absorption and deposition of MUFAs, and (iii) at high doses, sensory/pungent effects or metabolic stimulation may alter feed behaviour, gut motility or systemic energy partitioning, which could reduce net deposition of certain amino acids in muscle (Munglang and Vidyarthi, 2020; Dougnon et al., 2014; Elamin et al., 2015). The tissue-specific response (breast vs thigh) likely reflects intrinsic metabolic differences: white (breast) muscle is glycolytic with lower oxidative capacity, whereas thigh muscle has higher oxidative metabolism and different lipid turnover, affecting how dietary lipids and antioxidants are deposited and preserved.

The present results are broadly consonant with Adegoke et al. (2022, 2023), who reported improved technological traits and modified lipid profiles in broilers fed cayenne pepper powders, and with the review by Munglang and Vidyarthi (2020) summarizing dose-dependent effects of red pepper on broiler performance and meat quality. Dougnon et al. (2014) and Elamin et al. (2015) similarly observed improvements in biochemical indices and lipid profiles with *C. frutescens* supplementation, while Corduk et al. (2013) reported beneficial effects of pepper essential oils on gut microbiota and performance. The specific increase in breast oleic acid and EPA parallels data reported by Ortolan et al. (2019) and Borges- Machado et al. (2024) who found favourable shifts in fatty acid composition following pepper-based interventions. On the other hand, the observed reduction of several essential amino acids at high supplementation levels has been less emphasized in previous reports and suggests the need for careful dose optimization; some earlier studies documented neutral or inconsistent amino acids effects, likely due to differences in pepper form (powder vs oleoresin), cultivar, basal diet composition and bird genotype.

From a practical standpoint, moderate inclusion levels of cayenne pepper (reflecting E1 - E2 range) appear to offer the best balance: preserving muscle essential amino acids content while improving or maintaining favourable unsaturated fatty acids proportions and not compromising carcass yield. Higher inclusion (E3 - E4) may further enhance MU FA deposition and carcass yield, but at the cost of reduced concentrations of several essential amino acids. Therefore, producers aiming to use *C. frutescens* as a functional feed additive should target moderate supplementation rates and consider interactions with basal diet fatty acids composition and amino acids supply. Future formulation work could evaluate combined strategies (e.g. pepper + protected amino acids or specific lipid sources) to maximize both amino acid retention and favourable lipid modification.

CONCLUSION

The present study demonstrated that dietary supplementation of broiler chickens (Ross 308) with cayenne pepper (*Capsicum frutescens* L.) exerts multifaceted effects on carcass yield, chemical composition, amino acids and fatty acids profiles, and meat colour. Carcass yield improved significantly at the highest supplementation level, while live body weight and carcass weight remained unaffected. Chemical analyses showed stable protein deposition but lower water content and slightly higher fat content in breast muscle at higher inclusion

levels. A hypocholesterolemic effect was observed in thigh muscle already at the lowest supplementation, suggesting an early metabolic response to pepper-derived bioactives. Amino acids profiling revealed that moderate supplementation preserved essential amino acids, whereas higher inclusion levels led to reductions in threonine, valine, methionine, leucine, and lysine, indicating a dose-dependent trade-off between beneficial lipid changes and protein deposition. The fatty acid composition of breast muscle improved through increased oleic acid, linoleic acid, and eicosapentaenoic acid, resulting in higher MUFA but lower PUFA proportions. These shifts suggest that cayenne pepper may enhance the nutritional value of broiler meat through favourable modification of lipid fractions. The addition of *C. frutescens*, also affected the color of the meat in the experimental groups, while the experimental groups did not show color changes compared to the control. Overall, the findings support the potential use of cayenne pepper as a natural phytogenic additive to improve carcass yield and meat quality of broiler chickens. However, the observed dose-dependent effects highlight the need for optimized supplementation strategies, where moderate inclusion rates appear most effective in maintaining amino acid balance while enhancing lipid quality and visual attributes of meat. Future research should focus on refining dosage levels and exploring synergistic effects with other dietary components to maximize both nutritional and technological benefits.

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