Effect of Dietary Curcumin on the Growth Performance, Serum Antioxidation and Meat Quality of Ducks (*Anas Platyrhynchos*)

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Abstract

Background: With increasing of duck meat among consumers, the demand for growth performance and the meat quality health of ducks is increasing. Dietary curcumin altered the growth performance and meat quality. However, study on the effect of dietary curcumin on the growth performance, serum antioxidation and meat quality of ducks. This study investigated effects of dietary curcumin given to ducks on the growth performance, antioxidation capacity in plasma, meat quality, lipid oxidation and the concentration of volatile compounds in duck breast muscle. A total of 600 healthy ducks with similar body weight were randomly allotted into 4 groups with 10 replicates per group and 15 ducks per replicate. Ducks were fed experimental diets which the curcumin supplemental levels were 0, 300, 400 and 500 mg curcumin/kg basic feed, respectively. The experiment lasted for 10 weeks.

Results: Results showed that dietary supplementation of curcumin at levels 300, 400 and 500 mg/kg dietary ($P < 0.05$) improved the average final body weight. The ducks fed the basal diet without curcumin supplementation had the lowest FI ($P > 0.05$) and highest FCR ($P > 0.05$) among all ducks. Feeding ducks on diets supplemented with curcumin at each level significantly increased ($P < 0.05$) plasma activity of T-SOD and GSH-Px, and significantly reduced plasma MDA concentration compared to the control group. The dietary curcumin significantly increased the growth performance and the antioxidation capacity in plasma of ducks. Dietary curcumin improved the meat quality of ducks by significantly increasing pH₄₅, pH₂₄ ($P < 0.05$) and color of duck meat ($P < 0.05$), and significantly decreasing cooking loss ($P < 0.05$), shear force ($P < 0.05$), and the lipid oxidation of duck meat. 56 volatile compounds were identified and quantified. Interestingly, cantharidin among volatile compounds was firstly found in duck muscle, and only existed in the group of 500 mg curcumin/kg diet.

Conclusions: In conclusion, the supplementation of duck diets with curcumin at 300, 400, and 500 mg/kg diet improved growth performance, antioxidant status and meat quality of ducks. The cantharidin was firstly found in duck breast muscle when the dietary curcumin inclusion of 500 mg/kg.

Background

Duck meat is abundantly consumed in the world, especially in Asia because of its desirable nutritional characteristics [1]. But the duck meat is very susceptible to oxidation during storage owing to a high content of polyunsaturated fatty acids and essential amino acids. As an encouraging way to improve the animal antioxidation capacity and meat quality, or to prolong meat shelf-life, antioxidants supplemented in dietary has been used in livestock and poultry breeding, such as hens laying [2], chicken [3] and finishing pig [4].

Supplementation of a certain amount of antioxidants in dietary is an indispensable technique in the modern livestock and poultry farming industry. The natural antioxidants, especially polyphenol compounds, are the hot research topic owing to their ability to add the additional benefits to animal health and meat products. Curcumin is a kind of polyphenol component occurring in turmeric rhizomes (*Curcuma Longa* Linn). Curcumin has been equivocally proved to possess many beneficial biological functions, such as anticoccidial [5], anti-inflammatory [6], anticancer [7] and antioxidation ability protecting the cells against the lipid oxidation [1, 8]. The significant biological properties of curcumin render it a functional feed additive used in livestock feed. Curcumin had been authorized as a coloring and flavoring agent and antioxidation additive in food by the U.S.

Food and Drug Administration (FDA) since 1994 [9]. Curcumin was also used in livestock as a feed additive [10]. Many studies showed that curcumin supplemented in feed improved the growth performance of animals, such as ducks [11, 12], chickens [13], weaned piglets [14] and fishes [15].

Curcumin is an effective phenolic antioxidant, donating H-atoms from the phenolic group. Curcumin showed excellent performance in improving the antioxidant capacity of animals. In vitro study found that curcumin significantly decreased MDA content, and increased T-SOD activity in a time- and dose-dependent manner [16]. In vivo analysis in mice revealed that curcumin could upregulate various antioxidant enzymes, such as GR and NQO1 [17]. Oral administration of curcumin protected the liver against CCl₄-induced injury of rat by attenuating hepatic oxidative stress demonstrated by increasing the level of total hepatic GSH (γ -glutamyl-cysteinylglycine) and improving the ratio of hepatic GSH/GSSG (oxidized GSH) [18]. Dietary supplementation with curcumin at 100 to 300 mg/kg improved the antioxidant capacity of broilers, thereby subsequently maintaining the integrity of the cell membrane and increasing the water holding capacity, which resulted in meat quality improvement [19]. Turmeric rhizome powder (5 mg/kg) supplementation in diet given to chickens significantly enhanced antioxidant properties of chicken thigh meat by decreasing the malondialdehyde (MDA) content during storage (1, 3 and 7 days at 4 °C), and maintained the concentration of volatile compounds, such as aldehydes, ketones, alcohols, acids, esters, so as to increase the thigh meat shelf-life storage and quality in broiler chickens after slaughter [20].

However, there are no reports on the influence of dietary curcumin on the antioxidation property and meat quality of duck. In this study, the appropriate concentration in dietary curcumin and its effect on the growth performance, antioxidation property, and meat quality and the concentration of volatile compounds in breast muscle of duck were investigated.

Materials And Methods

Birds and husbandry

The experimental protocol was conducted in accordance with the practices outlined in the Guide for the Care and Use of Agricultural Animals in Agriculture Research and Teaching of Northeast Agricultural University (Protocol number: NEAU-[2011]-9).

A total of 600 1-day-male duck (*Anas Platyrhynchos*) with no significant different weight were purchased from a commercial hatchery and randomly assigned to 4 groups (Table 1), with 10 replicate pens (cages) per group and 15 ducks per pen for a 70-day feeding trial. The basal diets for the three stages (days 1–28, days 29–56 and days 57–70) were formulated according to National Research Council (1994) [21]. The control group birds (T0) were fed a corn-soybean basal diet (Table 2) for a 70-day, the other three groups were fed this diet supplemented with 300 mg/kg (T300), 400 mg/kg (T400) and 500 mg/kg (T500) curcumin, respectively. The birds were provided with ad libitum access to water and powdered diets. Daylight was eliminated but 24-h constant-light schedule was provided from incandescent bulbs. The house was maintained at 30°C to 32°C with a relative humidity of 60–70% at the first 3 days of age. Ambient temperature was gradually reduced by 2 °C to 3 °C every week to a final temperature of 26 ± 1°C and with a relative humidity of 50–55%.

Table 1
Experiment design.

Groups	Basal diet	Curcumin (mg curcumin /Kg basal diet)
T0	corn-soybean	0
T300	corn-soybean	300
T400	corn-soybean	400
T500	corn-soybean	500
T0: the group fed with the con-soybean basal diet; T300: the group fed with the con-soybean basal diet + 300 mg/kg curcumin; T400: the group fed with the con-soybean basal diet + 400 mg/kg curcumin; T500: the group fed with the con-soybean basal diet + 500 mg/kg curcumin.		

Table 2
Ingredient composition and nutrient content of the basal diet (% , as-fed basis).

Items	1–4 weeks	5–8 weeks	9–10 weeks
Ingredient			
Corn (7.9)	61.70	68.94	75.80
Soybean meal (45)	26.09	26.80	20.10
Corn protein flour (55)	7.90	—	—
Dicalcium phosphate	1.40	1.40	1.40
Limestone	1.08	1.06	1.06
Salt	0.38	0.38	0.38
DL-Methionine	0.15	0.22	0.16
L-Lysine	0.20	0.10	0.00
choline chloride (50%)	0.10	0.10	0.10
Premix	1.00 ¹	1.00 ²	1.00 ³
Total	100	100	100
Nutritional level			
Calculated nutrient ⁴			
Metabolizable energy (MJ/kg)	12.14	11.98	12.21
CP (%)	20.67	17.51	15.03
Calcium (%)	0.90	0.90	0.88
Total phosphorus (%)	0.68	0.67	0.65
Non-phytate phosphorus (%)	0.44	0.44	0.44
Lysine (%)	1.07	0.95	0.71
Methionine (%)	0.48	0.48	0.39
Methionine + cystine (%)	0.81	0.75	0.63
Threonine (%)	0.75	0.66	0.56
Tryptophane (%)	0.21	0.19	0.16
¹ The premix provided per kilogram diet: vitamin A 4000 IU, vitamin D3 2000 IU, vitamin E 20 mg, vitamin K3 2.0 mg, vitamin B1 2.0 mg, vitamin B2 12 mg, vitamin B6 3.0 mg, vitamin B12 0.02 mg, nicotinic acid 50 mg, D-pantothenic acid 10 mg, folic acid 1 mg, biotin 0.2 mg, Cu 8 mg, Fe 60 mg, Mn 100 mg, Zn 60 mg, Se 0.2 mg, I 0.4 mg.			

Items	1–4 weeks	5–8 weeks	9–10 weeks
² The premix provided per kilogram diet: vitamin A 3000 IU, vitamin D3 2000 IU, vitamin E 10 mg, vitamin K3 2.0 mg, vitamin B1 1.5 mg, vitamin B2 8 mg, nicotinic acid 30 mg, D-pantothenic acid 10 mg, vitamin B6 3.0 mg, vitamin B12 0.02 mg, biotin 0.1 mg, folic acid 1 mg, Cu 8 mg, Fe 60 mg, Mn 80 mg, Zn 40 mg, Se 0.2 mg, I 0.4 mg.			
³ The premix provided per kilogram diet: vitamin A 2500 IU, vitamin D3 1000 IU, vitamin E 10 mg, vitamin K3 2.0 mg, vitamin B1 1.5 mg, vitamin B2 8 mg, nicotinic acid 30 mg, D-pantothenic acid 10 mg, vitamin B6 3.0 mg, vitamin B12 0.02 mg, biotin 0.1 mg, folic acid 1 mg, Cu 8 mg, Fe 60 mg, Mn 80 mg, Zn 40 mg, Se 0.2 mg, I 0.3 mg.			
⁴ Values were calculated based on the data provided by Feed Database in China (2004).			

Sample collection

Ducks body weight and feed intake (FI) were recorded during the experiment and then feed conversion ratio (FCR) was calculated. At 70 D of age, one bird near average body weight was selected and slaughtered from per pen after all ducks were fasted for 12 h. The blood sample was collected from the wing veins into heparin sodium tuber. Blood samples were centrifuged at $3,000 \times g$ for 5 min at 4°C and the obtained plasma was stored at -20°C for analyzing. The right breast muscle of duck was obtained and analyzed for meat quality.

Assay of antioxidant enzyme activities in plasma

Plasma levels of total antioxidant capacity (T-AOC), total superoxide dismutase (T-SOD), glutathione peroxidase (GPx) and malondialdehyde (MDA) were measured by assay kits (Nanjing Jiancheng Bioengineering Institute, Nanjing, China), respectively, with UV-VIS Spectrophotometer (UV1100, MAPADA, Shanghai, China).

pH and color of duck breast muscle

The pH value of right breast muscle was measured by direct insertion of pH meter electrode (HI9125; Hanna Instruments, Padova, Italy) at 45 min and 24 h after slaughter. The meat color was measured at 45 min and 24 h after slaughter by a colorimeter (Minolta CR-400; Konica Minolta, Tokyo, Japan) using the CIE LAB trichromatic system as L* (lightness), a* (redness), and b* (yellowness), and the average color was obtained via 3 times measuring on the same muscle.

Measurement of drip loss percentage

The breast muscle was weighted after slaughter and suspended in a foam box, and kept 24 h at 4°C, and then the breast muscle was weighted again. The drip loss percent was evaluated as follows:

$$\text{Dripping loss (\%)} = \frac{W_1 - W_2}{W_1} \times 100$$

Where W_1 was the original weight of the breast muscle after slaughter (g), W_2 was the breast muscle after the loss of natural dripping water at 4°C for 24 h.

Measurement of cooking loss percentage

Cooking loss is considered as a crucial indicator to evaluate the water holding capacity of breast muscle, and was measured as described by Xiong et al. [22]. The breast muscle was cut and weighted accurately before cooking and cooked in a thin-walled plastic bag with × 10 cm (width) × 15 cm (length) individually in a water bath set at 85°C until the internal meat temperature reached 75°C measured by an insertable digital thermometer (MITIR TP600) with stainless steel probe. After cooling to the room temperature (25°C), the cooked muscle surface water was wiped with four layers filter paper, and then weighted immediately. The cooking loss was measured as follows:

$$\text{Cooking loss (\%)} = \frac{\text{Raw weight} - \text{Cooking weight}}{\text{Cooking weight}} \times 100$$

Shear force measurement

Shear force of duck breast muscle was measured according to Wang et al. [23] with some modification. The meat samples were cooled to 4°C after cooking. Two strips with 1.27 mm × 10 mm × 10 mm were cut parallel to the muscle fibers for test. The shear force was conducted by using a tenderization analyzer (C-LM3B tenderization instruments, Northeast Agricultural University, Heilongjiang, China) with a 25 kg load transducer, a crosshead speed of 200 mm/min. The most force value was recorded as the shear force when the duck breast samples were cut.

Thiobarbituric acid reactive substance (TBARS) assay

The TBARS was measured according to the method of Han et al. [24]. The lipid oxidation of duck breast muscle was represented by the TBARS value, and expressed as mg of malondialdehyde (MDA) per kg of duck breast muscle. It is calculated as follows:

$$\text{TBARS (mg/kg)} = \frac{A_{532}}{W_s} \times 9.48$$

Where A532 was the absorbance of the solution measured at 532 nm, W_s was the duck breast meat weight (g), and “9.48” was a constant originated from the dilution factor and the molar extinction coefficient (1.52 × 10⁵ M⁻¹ cm⁻¹) of the thiobarbituric acid (TBA) reaction product.

Carbonyl groups content assay

The carbonyl content of myofibrillar protein was detected with 2,4-dinitrophenylhydrazine (DNPH) according to Rababah et al. [25]. The absorbance of the solution at 370 nm was determined to quantify the carbonyl group content expressed as nmol DNPH incorporated mg⁻¹ meat.

Analysis of volatile compounds

Volatile compounds of duck breast muscle were extracted by solid phase micro-extraction (SPME) in the 20 ml headspace vial (CNW Technologies, Germany) with 3.00 g breast muscle samples according to Wen et al. [26]

with mini modification. The headspace vial with 3.00 g breast muscle sample and 4 μ L internal standard (IS) substance (100 ppm of o-dichlorobenzene dissolved in methanol) was sealed with PTFE/silicone septum. After equilibrating for 25 min at 45°C, a SPME fiber coated with 75 μ m carboxen /polydimethylsiloxane (CAR / PDMS) fiber was inserted into the sample through the septum and exposed to the headspace of the SPME vial for extraction at 45 °C for 40 min. After extraction, the PDMS/DVB/CAR fiber was immediately inserted into the injection port and was then thermally desorbed at 230°C for 3 min.

A gas chromatography/mass spectrometry (GC/MS) system (QP2020 Shimadzu, Kyoto, Japan) with an InertCapWaX (60 mm $\times$ 0.25 mm $\times$ 0.25 μ m) capillary column was used to analyze the volatile compounds in muscle. Helium as a carrier gas was introduced at a flow rate of 1.0 mL/min. After desorption, the oven temperature was maintained at 40 °C for 2 min, then raised to 60°C at 5 °C/min, 100 °C at a rate of 10 °C/min and ultimately 240 °C at a rate of 18 °C/min for 6 min. The ion source temperatures were 230 °C, and the mass spectrometer scanned from 33 to 450 of the m/z ratios. Identified results were obtained with the semblance degree > 90%. The volatile compounds were semi-quantified by dividing the peak areas of the target compounds by the peak area of the IS and multiplying this ratio by the initial content of the IS (expressed as ng/g).

Statistical analysis

The experiment data were obtained by least six times and analyzed statistically using one-way ANOVA by SPSS (Version 22.0, SPSS Inc., Chicago, USA) with 5% probability of error using the Duncan's multiple comparison among different groups. Statistical significance was $P < 0.05$. Orthogonal polynomial contrasts were used to determine linear and quadratic responses of *Anas Platyrhynchos* to different dose levels (0, 300, 400, 500 mg/Kg) of supplemental curcumin.

Results

Growth performance

Effect of dietary curcumin on weight gain (WG), FI, and FCR of ducks was shown in Table 3. Dietary curcumin significantly increased the WG of ducks in the curcumin groups than that in the control groups and displayed a liner and quadratic dose response ($P < 0.05$). There was no significant statistical difference among groups for FI and FCR.

Table 3
Effects of dietary curcumin on growth performance of ducks.

Items	Groups				SEM	P-value	P	
	T0	T300	T400	T500			Liner	quadratic
WG, g	1221.57 ^b	1308.04 ^a	1319.28 ^a	1328.14 ^a	33.33	0.016	0.001	0.005
FI, g	4798.21	4966.66	5008.50	4873.78	239.54	0.818	0.562	0.653
FCR, g/g	3.93	3.80	3.79	3.67	0.13	0.301	0.061	0.170
T ₀ : the control diet (without curcumin); T ₃₀₀ , T ₄₀₀ and T ₅₀₀ : 300, 400, 500 mg of curcumin/kg of feed, respectively.								
WG, FI and FCR represent means of 6 replicates in each group.								
WG = weight gain; FI = feed intake; FCR = feed conversion ratio.								
SEM = Standard error of the means.								
Results were means with n = 150 per group.								

Levels of plasma antioxidant enzyme activities

The effects of dietary curcumin on the antioxidant enzyme activities in plasma of ducks were presented in Fig. 1. Dietary curcumin increased the T-AOC content in plasma of ducks with no significant effects (Fig. 1A). Dietary curcumin linearly and quadratically enhanced the T-SOD (Fig. 1B) and GSH-Px (Fig. 1C) activity. The MDA content in plasma of ducks was decreased with a liner and quartic dose response ($P < 0.001$) (Fig. 1D).

Meat quality

Effects of dietary curcumin on duck meat quality were summarized in Fig. 2. Dietary curcumin supplementation decreased linearly ($P < 0.001$) and quadratically ($P < 0.001$). pH₄₅ of duck breast muscle decreased linearly ($P < 0.001$), and the pH₂₄ also decreased linearly ($P < 0.05$) and quadratically ($P < 0.05$). For meat color, the a* values of duck breast muscle at 45 min and 24 h increased with a linear and quadratic dose response ($P < 0.001$), whereas, no significant effects on L* and b* values at 45 min and 24 h in duck breast muscle among groups ($P > 0.05$). There was no significant effects of dietary curcumin on dropping loss in duck breast muscle when subjected to storage at 4°C for 24 h ($P > 0.05$). However, cooking loss and shear force of duck breast muscle decreased flowing the dietary curcumin supplementation and displayed a linear and quadratic dose response ($P < 0.001$).

Changes of TBARS values

Effects of dietary curcumin on the TBARS value of duck breast muscle when subjected to storage (at 4°C for 24 h) after slaughter was shown in Fig. 3(A). The TBARS values of duck breast muscle decreased linearly ($P < 0.001$) and quadratically ($P < 0.001$) flowing the dietary curcumin supplementation.

Carbonyl content

The carbonyl content in duck breast muscle when subjected to storage (at 4°C for 24 h) after slaughter was displayed in Fig. 3(B). Dietary curcumin significantly decreased the carbonyl content in duck breast muscle linearly ($P < 0.001$) and ($P < 0.001$) following the dietary curcumin supplementation.

Volatile compounds in duck breast muscle

As shown in Table 4, a total of 56 volatile compounds were identified in SPME extract of duck breast muscle by the means of GC/MS. These volatile components were categorized into 12 chemical classes, including 12 aldehydes, 2 ketones, 11 alcohols, 10 acids, 9 esters, 3 alkenes, 2 alkanes, 1 cantharidin, 3 silicidés, 1 alanine, 1 furan and 1 sulfide, allyl methyl (Table 4). These substances were mostly generated from hydrolysis (or oxidation) of lipid and protein, carbohydrate metabolism and spices.

Table 4
Concentration (ng/g) of volatile compounds identified and quantified by gas chromatography/mass spectrometry in duck breast muscle with different concentration of dietary curcumin.

Volatile compounds (ng/g)	Groups				SEM	P- value	P- value		CAS
	T ₀	T ₃₀₀	T ₄₀₀	T ₅₀₀			linear	quadratic	
Aldehydes									
Nonanal	22.15 a	6.93 b	6.83 b	6.51 ^b	0.194	< 0.001	0.027	< 0.001	124-19-6
Hexanal	20.49 a	15.49 b	10.65 c	3.16 d	0.275	< 0.001	0.000	< 0.001	66-25-1
Benzaldehyde	2.93 a	0.00 b	0.00 b	0.00 b	0.045	< 0.001	0.033	< 0.001	100-52-7
Hexadecanal	2.82 a	0.00 b	0.00 b	0.00 b	0.043	< 0.001	0.033	< 0.001	629-80-1
Tetradecanal	4.21 a	0.00 b	0.00 b	0.00 b	0.037	< 0.001	0.033	< 0.001	124-25-4
Pentadecanal	4.70 a	0.00 b	0.00 b	0.00 b	0.010	< 0.001	0.033	< 0.001	2765-11-9
2-Octenal, (E)-	6.66 a	0.00 b	0.00 b	0.00 b	0.061	< 0.001	0.033	< 0.001	2548-87-0
2-Decenal, (E)-	3.33 a	0.00 b	0.00 b	0.00 b	0.201	< 0.001	0.035	< 0.001	3913-81-3
2,4-Nonadienal, (E,E)-	2.90 a	0.00 b	0.00 b	0.00 b	0.041	< 0.001	0.033	< 0.001	5910-87-2
2,4-Decadienal, (E,E)-	28.62 a	0.00 b	0.00 b	0.00 b	0.618	< 0.001	0.033	< 0.001	25152-84-5
2-Nonenal, (E)-	5.10 a	0.00 b	0.00 b	0.00 b	0.082	< 0.001	0.033	< 0.001	18829-56-6
Benzaldehyde, 3-hydroxy-4-methoxy-	3.40 a	0.00 b	0.00 b	0.00 b	0.082	< 0.001	0.033	< 0.001	621-59-0
Ketones									
2,3-Octanedione	60.07 a	24.49 b	20.33 c	17.02 d	1.297	< 0.001	0.008	< 0.001	585-25-1

T₀: the control diet (without curcumin); T₃₀₀, T₄₀₀ and T₅₀₀: 300, 400, 500 mg curcumin/kg feed, respectively. Different uppercase letters were statistically significant ($P \leq 0.05$) in different groups. SEM = Standard error of the means. Orthogonal polynomials were used to investigate linear and quadratic responses to the level of curcumin treatment. Results are means with n = 6 per group.

Volatile compounds (ng/g)	Groups				SEM	P- value	P - value		CAS
	T ₀	T ₃₀₀	T ₄₀₀	T ₅₀₀			linear	quadratic	
Acetoin	3.82 a	3.56 b	3.50 b	2.83 c	0.057	< 0.001	< 0.001	< 0.001	513-86-0
Alcohols									
1-Pentanol	3.61 d	4.91 c	4.15 b	7.80 a	0.100	< 0.001	0.006	0.002	71-41-0
1-Hexanol	3.30 a	3.17 b	3.71 c	7.32 d	0.111	< 0.001	< 0.001	< 0.001	111-27-3
1-Octen-3-ol	42.20 d	43.93 c	44.93 b	46.03 a	0.142	< 0.001	< 0.001	< 0.001	1832-68-4
1-Octanol	5.75 a	2.44 b	2.37 c	2.67 c	0.076	< 0.001	< 0.001	< 0.001	111-87-5
Cyclooctyl alcohol	0.00 b	0.00 b	0.00 b	2.82 a	0.043	< 0.001	0.033	< 0.001	696-71-9
3-Octanol, 2-methyl-	2.71 d	3.55 c	8.46 b	12.54 a	0.217	< 0.001	< 0.001	< 0.001	26533-34-6
1-Hexanol, 2-ethyl-	4.74 a	2.72 b	2.61 b	2.24 c	0.089	< 0.001	< 0.001	< 0.001	104-76-7
Cyclohexanol, 4-(1,1-dimethylethyl)-	5.60 c	5.72 c	11.91 a	11.32 b	0.241	0.002	0.002	0.003	98-52-2
2-Decen-1-ol, (E)-	2.49 d	5.52 c	5.80 b	7.81 a	0.081	< 0.001	< 0.001	< 0.001	18409-18-2
trans-2-Undecen-1-ol	2.87 c	2.94 b	3.82 b	5.52 a	0.084	< 0.001	< 0.001	< 0.001	75039-84-8
2,3-Butanediol	3.23 d	3.47 c	6.01 b	7.00 a	0.069	< 0.001	< 0.001	< 0.001	513-85-9
Acids									
Butanoic acid	4.61 a	2.33 b	1.92 c	1.61 d	0.087	< 0.001	0.004	< 0.001	107-92-6
Hexanoic acid	6.95 a	6.01 b	5.72 c	5.69 c	0.096	0.002	0.007	< 0.001	142-62-1

T₀: the control diet (without curcumin); T₃₀₀, T₄₀₀ and T₅₀₀: 300, 400, 500 mg curcumin/kg feed, respectively. Different uppercase letters were statistically significant ($P \leq 0.05$) in different groups. SEM = Standard error of the means. Orthogonal polynomials were used to investigate linear and quadratic responses to the level of curcumin treatment. Results are means with n = 6 per group.

Volatile compounds (ng/g)	Groups				SEM	P- value	P - value		CAS
	T ₀	T ₃₀₀	T ₄₀₀	T ₅₀₀			linear	quadratic	
Octanoic acid	3.2	3.24	3.13	3.23	0.083	< 0.001	0.857	0.746	124-07-2
Nonanoic acid	3.23 a	2.48 b	2.40 c	2.18 d	0.026	< 0.001	0.001	0.000	112-05-0
n-Decanoic acid	5.14 b	5.55 a	4.56 c	4.58 c	0.019	< 0.001	0.016	0.055	334-48-5
Benzoic acid	6.71 a	4.12 b	3.59 c	2.53 d	0.055	< 0.001	< 0.001	0.000	65-85-0
Dodecanoic acid	3.89	3.83	3.78	3.77	0.062	0.276	0.044	0.146	143-07-7
n-Hexadecanoic acid	21.37 a	17.89 b	15.17 c	14.02 d	0.081	< 0.001	< 0.001	< 0.001	57-11-4
Tetradecanoic acid	2.17 a	0.00 b	0.00 b	0.00 b	0.009	< 0.001	< 0.001	< 0.001	544-63-8
Acetic acid	6.58 a	6.57 a	6.27 b	5.20 c	0.088	< 0.001	< 0.001	< 0.001	64-19-7
Esters									
Hexanoic acid, methyl ester	10.89 a	7.48 b	7.52 b	7.13 b	0.339	< 0.001	< 0.001	< 0.001	6624-60-8
Nonanoic acid, methyl ester	0.00 c	3.22 b	4.72 a	4.80 a	0.084	< 0.001	< 0.001	< 0.001	1731-84-6
Octanoic acid, methyl ester	6.33 c	7.80 b	7.99 ab	8.09 a	0.092	< 0.001	0.010	< 0.001	10152-76-8
iso-Amyl levulinate	8.41 d	9.02 c	10.62 b	17.71 a	0.124	< 0.001	0.005	< 0.001	71172-75-3
9-Octadecenoic acid, methyl ester, (E)-	3.63 b	5.30 a	5.14 a	5.18 a	0.095	< 0.001	0.003	0.009	22147-34-8
1,2-Benzenedicarboxylic acid, bis(2-methylpropyl) ester	3.01 c	3.29 b	3.38 b	4.91 a	0.077	< 0.001	0.005	0.000	84-69-5

T₀: the control diet (without curcumin); T₃₀₀, T₄₀₀ and T₅₀₀: 300, 400, 500 mg curcumin/kg feed, respectively. Different uppercase letters were statistically significant ($P \leq 0.05$) in different groups. SEM = Standard error of the means. Orthogonal polynomials were used to investigate linear and quadratic responses to the level of curcumin treatment. Results are means with n = 6 per group.

Volatile compounds (ng/g)	Groups				SEM	P- value	P- value		CAS
	T ₀	T ₃₀₀	T ₄₀₀	T ₅₀₀			linear	quadratic	
9-Hexadecenoic acid, methyl ester, (Z)-	2.71 c	3.19 a	2.80 b	3.21 a	0.038	< 0.001	0.026	0.089	1120-25-8
9,12-Octadecadienoic acid (Z,Z)-, methyl ester	3.52 d	5.44 b	4.69 c	5.64 a	0.059	< 0.001	< 0.001	0.001	112-63-0
Hexadecanoic acid, methyl ester	4.52 b	4.55 b	4.56 b	5.10 a	0.045	< 0.001	0.023	< 0.001	112-39-0
Alkenes									
2-Octen-1-ol, (E)-	6.03 d	10.39 c	11.42 b	14.13 a	0.13	< 0.001	< 0.001	< 0.001	18409-17-1
Anethole	0.00 c	0.00 c	2.38 b	5.83 a	0.036	< 0.001	0.002	< 0.001	4180-23-8
Hexadecane	0.00 d	6.44 c	8.20 b	9.41 a	0.043	< 0.001	< 0.001	< 0.001	629-73-2
Alkanes									
Tetradecane	2.76 d	3.67 c	3.80 b	4.53 a	0.054	< 0.001	< 0.001	< 0.001	629-59-4
Octadecane	2.06 d	3.53 c	4.11 b	10.96 a	0.052	< 0.001	0.003	< 0.001	593-45-3
Cantharidin								< 0.001	
Cantharidin	0.00 b	0.00 b	0.00 b	3.80 a	0.041	< 0.001	0.033	< 0.001	56-25-7
Silicide									
Cycloheptasiloxane, tetradecamethyl-	43.14 a	11.47 b	10.79 c	6.01 d	0.257	< 0.001	< 0.001	< 0.001	107-50-6
Cyclooctasiloxane, hexadecamethyl-	8.11 d	6.39 c	5.73 b	5.34 a	0.096	< 0.001	< 0.001	< 0.001	556-68-3
Cyclononasiloxane, octadecamethyl-	25.30 a	16.52 b	13.77 c	0.00 d	0.367	< 0.001	< 0.001	< 0.001	556-71-8
Alanine									

T₀: the control diet (without curcumin); T₃₀₀, T₄₀₀ and T₅₀₀: 300, 400, 500 mg curcumin/kg feed, respectively. Different uppercase letters were statistically significant ($P \leq 0.05$) in different groups. SEM = Standard error of the means. Orthogonal polynomials were used to investigate linear and quadratic responses to the level of curcumin treatment. Results are means with n = 6 per group.

Volatile compounds (ng/g)	Groups				SEM	<i>P</i> - value	<i>P</i> -value		CAS
	T ₀	T ₃₀₀	T ₄₀₀	T ₅₀₀			linear	quadratic	
Alanine	0.00 b	0.00 b	0.00 b	7.32 a	0.123	< 0.001	0.033	< 0.001	56-41-7
Furan									
Furan, 2-pentyl-	2.44 d	3.60 c	3.90 b	4.27 a	0.089	< 0.001	< 0.001	< 0.001	3777-69-3
Sulfide									
Sulfide, allyl methyl	9.90	9.94	9.95	9.95	0.317	0.404	0.078	0.212	10152-76-8
T ₀ : the control diet (without curcumin); T ₃₀₀ , T ₄₀₀ and T ₅₀₀ : 300, 400, 500 mg curcumin/kg feed, respectively. Different uppercase letters were statistically significant ($P \leq 0.05$) in different groups. SEM = Standard error of the means. Orthogonal polynomials were used to investigate linear and quadratic responses to the level of curcumin treatment. Results are means with n = 6 per group.									

56 volatile compounds were also quantified by GC/MS method. As shown in Table 4, concentrations of aldehydes in breast muscle decreased linearly and quadratically following dietary curcumin supplementation ($P < 0.05$). Dietary curcumin decreased ketones concentrations and displayed a linear and quadratic dose response ($P < 0.05$). The concentrations of most kinds of alcohols (1-Hexanol, 1-Pentanol, 1-Octen-3-ol, Cyclostyle alcohol, 3-Octanol, 2-methyl, Cyclohexanol, 4-(1,1-dimethylethyl), 2-Decen-1-ol, (E)-trans-2-Undecen-1-ol, 2,3-Butanediol) increased following dietary curcumin supplementation ($P < 0.05$), besides three alcohols (1-Octanol and 1-Hexanol, 2-ethyl) concentrations decreased ($P < 0.05$). Acids in the breast muscle decreased linearly and quadratically ($P < 0.05$) with the dietary curcumin supplementation, except for octanoic acid and dodecanoic acid. Esters in the duck breast muscle increased following dietary curcumin supplementation and displayed a linear and quadratic dose response ($P < 0.05$). Silicic acid in the duck breast muscle decreased linearly and quadratically following dietary curcumin supplementation ($P < 0.05$). Other volatile compounds (alkenes, alkanes, alanine, furan and sulfide, allyl methyl) increased linearly and quadratically following dietary curcumin supplementation ($P < 0.05$). The cantharidin was only identified in samples of ducks fed with 500 mg/kg dietary curcumin.

Discussion

Dietary antioxidants were an encouraging way to improve the growth performance, antioxidation capacity and enhance meat quality of livestock and poultry. Many studies reported that dietary curcumin given to animals improved the average daily feed intake and average daily gain, and decreased feed: gain ratio. Ducks fed with dietary curcumin (400 mg/kg) + ochratoxin A (2 mg/kg) increased the body weight, average daily gain and average daily feed intake and decreased feed: gain from day 1 to day 21 compared to these ducks fed with ochratoxin A (2 mg/kg) [12]. Although there was no significant effect on feed intake (FI) of broilers (on 42-day), dietary curcumin (200 mg/kg) significantly improved body weight and feed conversion ratio [13]. Xun et al. [14] reported that dietary curcumin (300 or 400 mg/kg) increased the average daily gain of weaned piglets with no significant difference and significantly decreased feed/gain ratio. El-Hakim et al. [15] found that dietary

curcumin (200 mg/kg) significantly increased the weight again and final body weight of fishes compared to the control group fishes without feeding curcumin/kg. In this current study, dietary curcumin significantly increased WG, whereas, with no significant effects on FI and FRC for ducks given to dietary curcumin (T300, T400 and T500) compared to ducks given to basic feed (T0), which demonstrated that curcumin promoted duck production performance.

The antioxidant stability is very important to the health and meat quality of ducks. The antioxidation enzymes, such as T-AOC, T-SOD, GSH-Px and MDA are important components in the antioxidation system of bodies. Dietary curcumin could enhance antioxidant ability of laying hens under heat stress environmental conditions via increasing total superoxide dismutase (SOD) activity, total antioxidant capacity (T-AOC), catalase (CAT) and glutathione peroxidase (GSH-Px) activities [2]. The activities of GSH-Px and T-AOC in the jejunum mucosal of ducks which fed dietary curcumin increased linearly ($P < 0.001$) and quantically ($P < 0.001$), and the MDA content decreased linearly ($P < 0.05$) flowing the dietary curcumin supplementation [27]. A study of Zhai et al. [28] revealed that curcumin supplementation increased the activity of T-AOC ($P > 0.05$), T-SOD ($P < 0.05$) and GSH-Px ($P > 0.05$) as well as decreased the activity of MDA ($P < 0.05$) in duck liver, which was cause for protecting the liver from ochratoxin A (OTA) damage and improving the stability of body antioxidation system. Zhang et al. [29] found that the addition of curcumin (150 mg/kg) in the diet increased the activities of T-AOC, T-SOD and GSH-Px, whereas decreased the content of MDA in serum of broiler. In this study, dietary curcumin enhanced the activity of T-AOC, T-SOD, GSH-Px and numerically decreased the content of MDA in plasma of ducks of 70-day ages, All these studies proved that curcumin in animal feed can improve the antioxidant function of animals by increasing the activity of antioxidant enzymes in serum, plasma and meat.

Zhang et al. [30] found that the addition of curcumin in the diet given to broilers increased linearly and quadratically ($P < 0.05$) the redness values, decreased quadratically ($P < 0.05$) the drip loss at 24 h in broiler breast muscle, and decreased the cooking loss with no significant effects. Another study of Zhang et al. [31] displayed that adding curcumin in the diet given to pigs significantly decreased the drip loss at 24 h and 48 h and increased the redness values in leg meat of growing pigs. However, there is no report on improving effect of dietary curcumin on duck meat until now. In this study, dietary curcumin given to ducks significantly improved meat quality of duck, including pH, color, cooking loss and shear force of breast muscle (Fig. 2).

The degree of meat oxidation is usually measured by the two indicators: the TBARS value and the carbonyl content. The TBARS value is mainly used to measure secondary products of lipid oxidation and used as an important indicator to evaluate the lipid oxidation of meat. The carbonyl content is an useful index to access protein oxidation in meat and meat products. Partovi et al. [32] found that dietary nanocurcumin (300 mg/kg) significantly prevented the occurrence of lipid oxidation (decreased TBARS values) in the breast muscle of chicken infected with *Eimeria* than those subjected to *Eimeria* without medication. Galli et al. [33] also found that TBARS values were lower in meat of chicken in the curcumin group (50 mg/kg curcumin in the basic feed) than that in the control (fed basic feed) group. Similarly, dietary curcumin given to the quail in the cold stress decreased the TBARS values in the eggs [34]. Supplementation dietary curcumin (300 mg/kg) decreased the level of carbonyl contents in broiler chicken meat after storage (30 days at -18°C and 3 days at 4°C) [35]. Curcumin shows a significant inhibitory effect on reducing meat oxidation in different animal. However, the optimal addition dose of curcumin in different animal diets to inhibit meat oxidation needs to be explored. In this study, the addition of 300–500 mg curcumin in diet significantly reduced the TBARS values and carboxyl

content in duck meat (Fig. 3). The oxidation of lipid and protein in meat or meat products is accompanied by the production volatile compounds. Linear aldehydes, ketones, their corresponding alcohols, such as acids, esters, alkanes, were produced by lipid autoxidation in meat or its products. For example, oxidation of linoleic acid, n-6 and n-9 polyunsaturated fatty acid could produce hexanal, heptanal and nonanal, respectively [36], Alkanes were commonly generated from the molecular re-arrangement of peroxide in lipid autoxidation. Alcohols and acids were obtained from their corresponding aldehydes owing to the reduction and oxidation. In this current study, a total of 56 volatile compounds were found in samples of the duck breast muscle. Most of these volatile components in the duck breast muscle has been identified in Beijing roasted duck [37, 38]. As shown in Table 4, changes of 56 volatile compounds in duck breast muscle indicated that the lipid oxidation was inhibited effectively by dietary curcumin given to ducks. Findings of volatile compounds in this current study have been proved by the lower TBARS value and carbonyl content in duck breast muscle. During storage, amount of alcohols from lipid oxidation of duck breast muscle were higher in curcumin groups than that in the control group. However, the esters and acids concentration of duck breast muscle were lower may be that dietary curcumin increased the antioxidation of duck breast muscle then inhibited the lipid and protein oxidation. 1-octen-3-ol, a hydroperoxide degradation product of linoleic acid, was predominant during storage and provided a potent mushroom aroma [39]. Aldehydes were produced by oxidation of alcohols and secondary products in the lipid oxidation process. Nonanal and hexanal concentration significantly decreased linearly ($P < 0.001$) and quadratically ($P < 0.001$) because that hexanal may lead to a rancid aroma with at high contents in meat [40]. Furans had an important role to offer the meat aroma [41]. Furan, 2-pentyl- concentration of duck breast muscle increased in curcumin groups than that in the control group may be that curcumin is a spice in food, and furan, 2-pentyl- contributed sweet and butter flavors [42]. Interestingly, cantharidin was firstly found in duck breast muscle when 500 mg/kg dietary curcumin given to ducks. Cantharidin has been shown to have antitumor effect and considered as a potent anticancer small molecule to be developed. However, the generation mechanism in duck meat 500 mg/kg curcumin group needs to be further investigated.

Conclusions

In this study, dietary curcumin given to ducks at levels of 300–500 mg/kg diet significantly increased the growth performance and the plasma antioxidation capacity. Dietary curcumin improved the quality and the concentration of volatile compounds of duck meat. The present study provided a nutritional strategy for enhancing growth performance and improving breast muscle quality of ducks.

Abbreviations

WG

Weight Gain; FI:Feed Intake; FCR:Feed Conversion Ratio; T-AOC:Total Antioxidant Capacity; T-SOD:Total Superoxide Dismutase; GSH-PX:Glutathione Peroxidase; MDA:Malondialdehyde.

Declarations

Ethics approval and consent to participate

The experimental protocol was conducted in accordance with the practices outlined in the Guide for the Care and Use of Agricultural Animals in Agriculture Research and Teaching of Northeast Agricultural University (Protocol number: NEAU-[2011]-9).

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed in this study are available from the corresponding author on reasonable request.

Competing interests

The authors have no competing interests to declare.

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Author's contributions

JSJ and FXJ led experimental work, JSJ and wrote the first draft of the manuscript. YH and LFJ performed the feeding ducks for 70 day. ie. DXP reviewed the manuscript. PQ and LRQ performed the Thiobarbituric Acid Reactive Substance (TBARS) and carbonyl groups content assay. WM performed the meat quality of ducks. WYJ performed the antioxidation capacity in plasma of ducks. LMR and Xin Zhou performed the volatile compounds of duck breast muscle. SAS reviewed the manuscript. FXJ reviewed and edited the manuscript.

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Figures

Figure 1

Effects of dietary curcumin on the antioxidant enzymes activities in plasma of ducks. Bars in Fig. 1 represent the Mean $\pm$ SD (n=6). Different letters above bars means statistically significant ($P \leq 0.05$) in different groups. T₀: the control diet (without curcumin); T₃₀₀, T₄₀₀ and T₅₀₀: 300, 400, 500 mg of curcumin/kg of feed, respectively. Results are means with n = 6 per group.

Figure 2

Effects of dietary curcumin on the meat quality of duck breast muscle. Bars in Fig. 2 represent the Means $\pm$ SD (n=6). Different letters above bars means statistically significant ($P \leq 0.05$) in different groups. T0: the control diet (without curcumin); T300, T400 and T500: 300, 400, 500 mg of curcumin/kg of feed, respectively. Results are means with n = 6 per group.

Figure 3

Effects of dietary curcumin on the lipid oxidation of duck breast muscle. Bars in Fig. 3 represent the Means $\pm$ SD (n=6). Different letters above bars means statistically significant ($P \leq 0.01$) in different groups. T0: the control diet (without curcumin); T300, T400 and T500: 300, 400, 500 mg of curcumin/kg of feed, respectively. Results are means with n = 6 per group.