

Effects of taurine on growth performance, antioxidant capacity, and lipid metabolism in broiler chickens

H. L. Han, J. F. Zhang, E. F. Yan, M. M. Shen, J. M. Wu, Z. D. Gan, C. H. Wei, L. L. Zhang, and T. Wang¹

College of Animal Science and Technology, Nanjing Agricultural University, Jiangsu 210095, Nanjing, People's Republic of China

ABSTRACT To investigate the effects of dietary taurine supplementation on growth performance, antioxidant status, and lipid metabolism in broilers, 384 male broilers (Arbor Acres, 1 D of age) were randomly allocated into 4 groups with 8 replicates of 8 birds. Dietary treatments were supplemented with taurine at the level of 0.00, 2.50, 5.00, and 7.50 g/kg of the diet (denoted as CON, TAU1, TAU2, TAU3, respectively). The BW gain from 1 to 21 D and from 22 to 42 D were all increased linearly (linear, $P < 0.001$) by taurine supplementation. Throughout the trial period, the highest BW gain and favorable gain-to-feed ratio were observed in the TAU2 group. Taurine supplementation increased the antioxidant enzyme activities and decreased (linear, $P < 0.001$) the content of malondialdehyde in both serum and the liver of broilers and alleviated oxidative damage through enhancing ($P < 0.05$) the hepatic genes expression of nuclear factor erythroid-2-related factor 2 (*NRF2*), glutathione peroxidase (*GPX*), and heme oxygenase-1

(*HO-1*). Correspondingly, in serum, the activities of hepatic lipase and total lipase were decreased linearly and quadratically (linear and quadratic, $P < 0.001$) with the increasing inclusion of taurine in the diet. Meanwhile, in serum, the content of triglycerides was significantly decreased ($P < 0.05$), and except for TAU3, the total cholesterol content was also significantly decreased ($P < 0.05$) by taurine supplementation. In addition, the hepatic content of triglycerides was significantly decreased ($P < 0.05$) in the TAU1 and TAU2 groups. Compared with the CON group, the hepatic genes expression of adenosine monophosphate-activated protein kinase alpha (*AMPK α*), silent 1, (*SIRT1*) and carnitine palmitoyl-transferase 1 (*CPT-1*) were all increased ($P < 0.05$), and sterol regulatory element-binding protein-1 (*SREBP-1*) expression was decreased ($P < 0.05$) in the TAU2 group. These results indicated that taurine supplementation improved the growth performance, antioxidant capacity, and lipid metabolism of broilers.

Key words: taurine, chicken, growth, antioxidant capacity, lipid metabolism

2020 Poultry Science 99:5707–5717

<https://doi.org/10.1016/j.psj.2020.07.020>

INTRODUCTION

Broilers of modern intensive production are challenged by various disorders, infections, oxidative stress, and lipid accumulation (Zhang et al., 2009). It is well known that the excess levels of free radicals can lead to damage to cells. Under normal circumstances, body antioxidant systems could protect the body from the oxidative damage. Recent studies confirmed that peroxisome proliferator-activated receptor α (*PPAR α*) was implicated in the oxidative stress response and mediated the expression of several antioxidant genes to relieve oxidative stress, such as

superoxide dismutase (*SOD*) (Yu et al., 2008), glutathione peroxidase (*GPX*) (Chung et al., 2009), and heme oxygenase-1 (*HO-1*) (Kleinhenz et al., 2009). These results suggested that antioxidant capacity was associated with lipid accumulation (Furukawa et al., 2004). Lipid metabolism is a complex physiological process that is involved in nutrient regulation (Chu et al., 2014), hormone adjustment (Bandyopadhyay et al., 2015), and homeostasis (Palomer et al., 2013). In avian species, liver is the main site of de novo fatty acid synthesis, accounting for 90–95% in young chicks (Griffin, 1992). Excess lipid accumulation in the liver could lead to serious biological damage, several pathologic statuses, and even death (Fellenberg and Speisky, 2006). Therefore, evaluation of the lipid metabolism and antioxidant capacity of broiler chickens is crucial in preventing chicken disease and maintaining health.

Taurine is a non-nutritive feed additive. It is derived from biosynthesis in methionine and cysteine metabolism.

© 2020 Published by Elsevier Inc. on behalf of Poultry Science Association Inc. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Received January 10, 2020.

Accepted July 23, 2020.

¹Corresponding author: tianwangnjau@163.com

Numerous studies show that taurine exerts good antioxidant properties, included inhibiting lipoxygenase and prostaglandin synthetase activities, reducing lipid peroxidation (Huxtable, 1992), increasing antioxidant enzyme activity (Li et al., 2016), and scavenging reactive oxygen species. Nuclear factor erythroid 2-related factor 2 (NRF2) is a key regulator of the antioxidative defense pathway (Motohashi and Yamamoto, 2004). It was reported that the translocation of NRF2 from cytoplasm to the nucleus upregulated the expression of antioxidant enzymes (Singh et al., 2006; Dreger et al., 2010; Kim and Vaziri, 2010), indicating that the gene expression of antioxidant enzymes was governed by the NRF2 signaling pathway (Kobayashi et al., 2009). In addition, taurine has the biological function of reducing fat metabolism disorders and lipid accumulation in the liver (Chen et al., 2009; Das et al., 2012; Murakami, 2015). Many studies clarified that taurine plays a significant function in the metabolism of lipid, reduces hepatic and serum lipid accumulation, and improves the plasma levels of triglycerides (Gentile et al., 2011; Chang et al., 2011; Nardelli et al., 2011). Taurine supplementation reduced fat accumulation and decreased lipid levels in the plasma and liver in rats (Bonfleur et al., 2015). The reason may be that taurine stimulates the genes expression involved in lipid metabolism (Tsuboyama-Kasaoka et al., 2006), such as acetyl-CoA carboxylase (ACC), sterol regulatory element-binding protein-1c (SREBP-1c), and PPAR α (Davail et al., 2000).

Adenosine monophosphate-activated protein kinase (AMPK) and sirtuin 1 (SIRT1) are closely related to lipid metabolism and activate each other and then stimulate fatty acid oxidation and inhibit hepatic lipid accumulation (Cantó et al., 2009; Tessari et al., 2009; Ruderman et al., 2010). Previous studies have shown that taurine was able to enhance the phosphorylation of AMPK in murine white adipose tissue and adipocytes to improve lipid metabolic disorder (Guo et al., 2019). Phosphorylated AMPK can augment fatty acid oxidation, decrease glucose output, and affect total cholesterol (TC) and triglyceride (TG) synthesis (Hou et al., 2018). Moreover, taurine was reported to upregulate fatty acid oxidation and downregulate lipogenesis by inducing SIRT1 overexpression and thereby providing protection against hepatic steatosis induced by a high-fat diet (Calak et al., 2014). Based on the actions of taurine against metabolic disorders mediated by SIRT1 (Elwahab et al., 2017) or AMPK (Guo et al., 2019), we hypothesized that taurine may regulate lipid accumulation through the AMPK/SIRT1 pathway.

However, in broilers, no information has been available regarding the mechanisms involved in taurine actions on AMPK/SIRT1 pathway and lipid. Therefore, the present study aimed to provide a comprehensive analysis from both the serum and liver to evaluate the effects of dietary taurine on growth performance, antioxidant status, and lipid metabolism in broilers. The results of the present study will provide useful information about the role and mechanisms of taurine in lipid metabolism of broiler chickens.

MATERIALS AND METHOD

Experimental Animals, and Management

Taurine (purity > 98.5%) was purchased from Jian-gyin Huachang Food Biotechnology Co. Ltd. (Zhejiang, China). A total of 384 1-day-old similar weight (40.46 ± 0.07) male Arbor Acres broiler chicks were obtained from a local hatchery (Hewei Company, Anhui Province, China), and chicks were randomly allotted into 4 groups with 8 replicates of 12 birds each. Birds were fed mash corn-soybean meal based on diets supplemented with 0, 2.50, 5.00, and 7.50 g of previously prepared taurine per kg of the diet (denoted as CON, TAU1, TAU2, TAU3) for 42 D in 2 phases (1 to 21 D and 22 to 42 D), respectively. We measured the basal diet content of taurine performed by the Jiangsu provincial animal products quality testing center (Jiangsu, China) and performed as per the guidelines set by the document number 2483 of the Department of Agriculture (2016) of the national standards of the People's Republic of China, detailed as follows: diet samples were extracted by water and the protein precipitant, derivatization was performed using dansyl chloride, and all samples were analyzed using HPLC and external standard. All experimental diets were formulated to meet the NRC (1,994) recommendation for broilers, and its ingredients and compositions of diets used in experiment are listed in Table 1.

Housing

During the trial period, chicks had free access to feed and water with 23 h light and 1 h darkness per day. The chicks were weighed and placed in cages ($120 \times 60 \times 50$ cm; 0.09 m^2 per chick) and kept in 3-layer pens. Birds were vaccinated for Newcastle disease and infectious bronchitis. The temperature of the room was kept at 32°C to 35°C for the first 5 D, after which it declined by 3°C a wk until decreased to 22°C . The experimental procedures were in accordance with the guidelines set by the Institutional Animal Care and Use Committee of Nanjing Agricultural University.

Growth Performance Measurement

At 1, 21, and 42 D of age, BW and total feed consumption in each replicate were recorded to calculate BW gain (BWG), feed intake (FI), and the gain-to-feed ratio (G/F). The G/F was calculated as the ratio between BWG and FI.

Sample Collection

At 42 D of age, 1 bird (close to the average BW of each replicate) from each replicate was taken out for slaughter after a period of 12-h fasting. The blood sample from each animal was collected in a nonanticoagulant sterile blood vessel from the jugular vein. After blood sampling, the birds were euthanized by cervical dislocation

Table 1. Ingredient composition and nutrient contents of experimental diets.

Variables ¹	Starter period (1–21 D)				Grower period (22–42 D)			
	CON	TAU1	TAU2	TAU3	CON	TAU1	TAU2	TAU3
Ingredient (%)								
Corn	56.58	56.58	56.58	56.58	60.55	60.55	60.55	60.55
Soybean meal (44%, CP)	29.76	29.76	29.76	29.76	27.78	27.78	27.78	27.78
Corn gluten meal	4.96	4.96	4.96	4.96	3.47	3.47	3.47	3.47
Soybean oil	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97
Limestone	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19
Dicalcium phosphate	1.49	1.49	1.49	1.49	0.99	0.99	0.99	0.99
Alanine ²	0.54	0.36	0.18	0	0.54	0.36	0.18	0
Microcrystalline cellulose ³	0.21	0.14	0.07	0	0.21	0.14	0.07	0
The approximate content of taurine	<0.01	0.25	0.50	0.75	<0.01	0.25	0.50	0.75
Salt	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Premix ⁴	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Total	100	100	100	100	100	100	100	100
Calculated nutrient and energy level								
Apparent ME (MJ/kg)	12.52	12.52	12.52	12.52	12.92	12.92	12.92	12.92
CP (%)	21.6	21.6	21.6	21.6	20.01	20.01	20.01	20.01
Lysine (%)	1.18	1.18	1.18	1.18	1.06	1.06	1.06	1.06
Methionine (%)	0.52	0.52	0.52	0.52	0.45	0.45	0.45	0.45
Calcium (%)	1.08	1.08	1.08	1.08	0.96	0.96	0.96	0.96
Total phosphorus (%)	0.70	0.70	0.70	0.70	0.68	0.68	0.68	0.68
Available phosphorus (%)	0.46	0.46	0.46	0.46	0.39	0.39	0.39	0.39
Analyzed composition								
CP (%)	21.33	21.32	21.47	21.54	19.90	19.91	19.88	19.91
Crude fat (%)	4.81	4.82	4.78	4.84	6.52	6.57	6.58	6.54
Calcium (%)	1.00	1.04	1.00	1.00	0.93	0.94	0.95	0.94
Total phosphorus (%)	0.66	0.64	0.63	0.69	0.66	0.68	0.63	0.67

¹CON, basal diet; TAU1, TAU2 and TAU3 group, basal diet adding 2.50, 5.00, and 7.50 g/kg TAU, respectively.

²Alanine, the purity was 99%, was used to balance the nitrogen in all diets.

³Microcrystalline cellulose, the purity was 99%, was used to balance the different percentages of supplemental taurine.

⁴The premix provided per kg of diet: retinyl acetate for vitamin A, 10,000 IU; cholecalciferol for vitamin D₃, 3,000 IU; DL- α -tocopheryl acetate for vitamin E, 30 IU; menadione sodium bisulphate, 1.3 mg; thiamin, 2.2 mg; riboflavin, 8.0 mg; nicotinamide, 40 mg; choline chloride, 600 mg; calcium pantothenate, 10 mg; pyridoxine HCl, 4 mg; biotin, 0.04 mg; folic acid, 1 mg; vitamin B₁₂ (cobalamin), 0.013 mg; Zn, 60 mg; Fe, 80 mg; Cu, 8.0 mg; Mn, 110 mg; I, 1.1 mg; Se, 0.3 mg.

immediately, and the liver was isolated. Serum was obtained by centrifugation at 3,500 rpm for 15 min at 4°C in a centrifuge machine, the top serum in the tube was collected and stored at –80°C for analysis (Tian et al., 2019). The liver was dissected, weighed, and then homogenized and stored in liquid nitrogen for enzymatic activity and mRNA expression analysis before freezing for storage (–80°C).

Antioxidant Capacity Evaluation of Serum and the Liver

One gram of liver tissues preserved at –80°C was cut into small pieces and mixed with 9 mL of 0.9% ice-cold sodium chloride buffer for subsequent homogenization using an Ultra-Turrax homogenizer (Tekmar Co., Cincinnati, OH) to centrifuge at 3,500 rpm at 4°C for 10 min (Ge et al., 2019). The hepatic supernatant and serum were used to measure total antioxidant capacity (Kit code number: A015-2-1), SOD (Kit code number: A003-2-1), GPX (Kit code number: A002-1-1), glutathione (GSH; Kit code number: A001-2-1), catalase (CAT; Kit code number: A007-1-2) activities, and malonaldehyde (MDA; Kit code number: A007-3-1) content; the kits were purchased from Nanjing Jiancheng Institute of Bioengineering (Jiangsu, China) and the procedures were performed as per the manufacturer's instructions.

Analysis of Lipid Metabolism in Serum and the Liver

Serum levels of TC (Kit code number: A113-2-1), TG (Kit code number: A113-1-1), high-density lipoprotein cholesterol (HDL-C; Kit code number: A112-1-1), low-density lipoprotein cholesterol (Kit code number: A112-1-2), and nonesterified fatty acid (NEFA; Kit code number: A042-2-1) and total lipase (TL; Kit code number: A065-1-1), hepatic lipase (HL; Kit code number: A065-1-1), and lipoprotein lipase (LPL; Kit code number: A065-1-1) activities were measured using the kits obtained from the Nanjing Jiancheng Institute of Bioengineering (Jiangsu, China). The liver samples stored in liquid nitrogen were used to make tissue homogenate, the hepatic TC (Kit code number: A113-2-1), TG (Kit code number: A113-1-1), and NEFA (Kit code number: A042-2-1) levels and TL (Kit code number: A065-1-1), HL (Kit code number: A065-1-1), and LPL (Kit code number: A065-1-1) activities in the liver were also measured using kits obtained from the Nanjing Jiancheng Institute of Bioengineering (Jiangsu, China). The hepatic fatty acid synthase (FAS, Kit code number: F7082-A), ACC (Kit code number: F7083-A), and hormone-sensitive triglyceride lipase (HSL; Kit code number: F7084-A) activities were measured using ELISA kits purchased from Shanghai Yili Biological Technology Co., Ltd. (Shanghai, China) and performed as per the manufacturer's protocol.

Table 2. Primer sequence of target and reference genes.

Gene name ¹		Primers sequence (5'-3')	Accession number
Antioxidant-related genes			
<i>NRF2</i>	Forward	GAGCCCATGGCCTTTCCTAT	NM_001007858.1
	Reverse	CACAGAGGCCCTGACTCAAAA	
<i>HO-1</i>	Forward	AACTTTCGCAGCCACACAAC	NM_205344.1
	Reverse	GACCAGCTTGAACCTCGTGGA	
<i>GPX</i>	Forward	GACCAACCCGCAGTACATCA	NM_001277853.1
	Reverse	GAGGTGCGGGCTTTCCTTTA	
<i>SOD1</i>	Forward	CCGCTTGTCTGATGGAGAT	NM_205064.1
	Reverse	TGCATCTTTTGGTCCACCGT	
<i>CAT</i>	Forward	GCGCCCCGAACTATTATCCA	NM_001031215.2
	Reverse	ATACGTGCGCCATAGTC	
Lipid metabolism genes			
<i>AMPKα</i>	Forward	GGGACCTGAAACCAGAGAACG	NM001039605.1
	Reverse	ACAGAGGAGGGCATAGAGGATG	
<i>SIRT1</i>	Forward	GATCAGCAAAAAGGCTGGATGGT	NM_001004767
	Reverse	ACGAGCCGCTTTCGCTACTAC	
<i>CPT-1</i>	Forward	ACAGCGAATGAAAGCAGGGT	NM_001012898.1
	Reverse	GCCATGGCTAAGGTTTTCGT	
<i>PPARα</i>	Forward	AGTAAGCTCTCAGAAACTTTGTTG	NM_001001464.1
	Reverse	AAGGTTGAAACAGAAGCCGC	
<i>APOA1</i>	Forward	CGCATTCGGGATATGGTGGA	NM_205525
	Reverse	GTCAAGCTGTTTGCCACAG	
<i>SREBP-1</i>	Forward	GACCATCCTGGCCACAGTAC	AF278697
	Reverse	TCTCAATGGCATTGTGGGGCT	
<i>FAS</i>	Forward	AGAGGCTTTGAAGCTCGGAC	NM_205155.2
	Reverse	GGTGCCGAATACTTGGGGCT	
<i>ACC</i>	Forward	TTGTGGCACAGAAGAGGGAA	NM_205505.1
	Reverse	GTTGGCACATGGAATGGCAG	
<i>ACTB</i>	Forward	TGCTGTGTTCCCATCTATCG	NM_205518.1
	Reverse	TTGGTGACAATACCGTGTTC	

¹Abbreviations: *ACC*, acetyl-CoA carboxylase; *ACTB*, beta-actin; *AMPK α* , adenosine monophosphate-activated protein kinase alpha; *ApoA1*, apolipoprotein A1; *CAT*, catalase; *SIRT1*, silent 1; *CPT-1*, carnitine palmitoyltransferase 1; *FAS*, fatty acid synthase; *GPX*, glutathione peroxidase; *HO-1*, heme oxygenase-1; *NRF2*, nuclear factor erythroid 2-related factor 2; *PPAR α* , peroxisome proliferator-activated receptor α ; *SOD1*, superoxide dismutase 1; *SREBP-1*, sterol regulatory element-binding protein-1.

RNA Extraction and Quantitative Real-Time PCR

Total RNA in the frozen liver samples was extracted using TRIzol Reagent (TaKaRa Biotechnology, Dalian, China; Kit code number: R601-01). The concentration and purity of RNA were quantified with a spectrophotometer (NanoDrop Technologies, Wilmington, DE) as per the readings at 260 and 280 nm. Subsequently, the RNA was reverse transcribed into cDNA using the PrimeScript RT Reagent Kit (Perfect Real Time; SYBR PrimeScriP TaKaRa, China; Kit code number: 3894A) as per the manufacturer's instructions. The cDNA samples were amplified by quantitative real-time PCR with SYBR Premix Ex Taq Reagents (TaKaRa Biotechnology). The real-time PCR cycling conditions were as follows: 95°C for 30 s, 40 cycles of 95°C for 5 s, and 60°C for 30 s (Lu et al., 2019). The mRNA expression of target genes relative to beta actin was calculated using $2^{-\Delta\Delta CT}$ method according to Livak and Schmittgen (2001). All of the primer sequences are listed in Table 2.

Statistical Analysis

All data were preliminarily processed using Excel 2010. The statistical analyses were performed using SPSS 22.0 statistical software (SPSS Inc., Chicago, IL)

with replicate as an experimental unit. Differences among treatments were examined using Duncan's multiple range test and orthogonal polynomial contrast test for linear and quadratic to evaluate the effects of taurine supplementation. Differences were considered as significant at $P < 0.05$.

RESULTS

Growth Performance

The effects of taurine supplementation on growth performance of broilers are shown in Table 3. The 21 D BW, 42 D BW, and BWG from 1 to 21 D and 22 to 42 D were all increased by taurine supplementation (linear, $P < 0.001$). Compared with the CON group, TAU2 increased G/F and FI from 22 to 42 D and 1 to 42 D ($P < 0.05$). Throughout the trial period, the highest BWG and favorable G/F were observed in the TAU2 group.

Liver and Serum Antioxidant Capacity

As shown in Table 4, broilers in taurine groups exhibited less content of MDA (linear, $P < 0.001$) and greater (linear, $P < 0.01$) activities of SOD, GPX, and GSH than the CON group in serum. In the liver, taurine

Table 3. Effects of dietary taurine at different levels on growth performance of broilers.

Items	Dietary taurine concentration treatment ³				SEM ¹	P Value	
	CON	TAU1	TAU2	TAU3		Linear ²	Quadratic ²
21 D BW, g	589.144 ^c	645.379 ^{a,b}	635.331 ^b	664.200 ^a	5.981	<0.001	0.062
42 D BW, g	1,870.420 ^b	1,990.649 ^a	2,042.854 ^a	2,037.254 ^a	16.578	<0.001	0.011
1–21 D							
BWG (g/bird)	548.766 ^c	604.916 ^{a,b}	594.852 ^b	623.688 ^a	5.968	<0.001	0.061
FI (g/bird)	835.574 ^b	855.081 ^{a,b}	877.602 ^{a,b}	898.719 ^a	9.836	0.017	0.966
G/F (g/g)	0.658	0.711	0.679	0.697	0.009	0.292	0.336
22–42 D							
BWG (g/bird)	1,281.276 ^b	1,345.270 ^{a,b}	1,407.523 ^a	1,373.054 ^a	14.399	0.005	0.056
FI (g/bird)	2,244.814 ^{b,c}	2,292.604 ^{a,b}	2,154.589 ^c	2,378.973 ^a	25.027	0.178	0.049
G/F (g/g)	0.571 ^b	0.590 ^b	0.653 ^a	0.578 ^b	0.009	0.143	0.001
1–42 D							
BWG (g/bird)	1,830.042 ^b	1,950.186 ^a	2,002.375 ^a	1,996.741 ^a	16.587	<0.001	0.011
FI (g/bird)	3,080.388 ^b	3,147.685 ^{a,b}	3,032.191 ^b	3,277.692 ^a	28.564	0.038	0.079
G/F (g/g)	0.594 ^b	0.621 ^b	0.660 ^a	0.610 ^b	0.006	0.042	<0.001

^{a-c}Means within the same row with no common superscript differ significantly ($P < 0.05$).

Abbreviations: BWG, BW gain; FI, feed intake; G/F, gain-to-feed ratio.

¹Standard error of the means ($n = 8$).

²Orthogonal polynomials were used to evaluate linear and quadratic responses to the levels of taurine treatment.

³CON, basal diet; TAU1, TAU2 and TAU3 group, basal diet adding 2.50, 5.00, and 7.50 g/kg TAU, respectively.

supplementation increased the activity of *GPX* (linear, $P = 0.004$) and decreased (linear, $P < 0.001$; quadratic, $P = 0.002$) the concentration of MDA. There was a linear increase in the content of GSH (linear, $P < 0.001$) by dietary taurine increase, and the content of GSH in taurine groups were greater ($P < 0.05$) than the CON group. The hepatic activity of total antioxidant capacity in the TAU2 group was greater than that in the CON group ($P < 0.05$).

Lipid Profile and Hepatic Enzyme Activities in Serum and the Liver

Compared with the CON group (Table 5), the serum level of TG in taurine groups were significantly decreased ($P < 0.05$), and except for TAU3, the TC level in serum was also significantly decreased ($P < 0.05$). In addition, the activities of HL and TL in the serum

decreased linearly and quadratically (linear and quadratic, $P < 0.001$) with the increasing inclusion of taurine in the diet. In the liver, compared with the CON group, moderate amounts of taurine in the diet decreased the level of TG ($P < 0.05$) and increased the activities of LPL, TL, and HSL ($P < 0.05$).

Gene Expression Levels of Antioxidant Capacity

As seen in Table 6, in comparison with the CON group, the mRNA expression levels of *NRF2* and *GPX* were increased ($P < 0.05$) in the TAU2 group, and the mRNA expression of *HO-1* was also increased in the TAU2 and TAU3 groups ($P < 0.05$). The mRNA expression levels of *SOD1* and *CAT* were not of significant difference in the liver of broilers among all the groups ($P > 0.05$).

Table 4. Effects of different levels of taurine on antioxidant function in serum and liver of broilers.

Items	Dietary taurine concentration treatment ³				SEM ¹	P Value	
	CON	TAU1	TAU2	TAU3		Linear ²	Quadratic ²
Serum							
T-AOC (U/mL)	12.873 ^b	14.014 ^{a,b}	14.199 ^a	14.060 ^{a,b}	0.210	0.043	0.116
SOD (U/mL)	106.365 ^b	127.796 ^a	123.059 ^a	123.285 ^a	1.825	<0.001	<0.001
<i>GPX</i> (U/mL)	224.016 ^c	241.721 ^b	256.230 ^a	237.541 ^b	2.861	0.006	<0.001
GSH (umol/L)	9.536 ^b	11.513 ^a	10.931 ^a	11.222 ^a	0.173	<0.001	0.001
CAT (U/mL)	8.424	8.740	8.604	8.446	0.067	0.909	0.084
MDA (nmol/mL)	10.949 ^a	10.486 ^{a,b}	10.116 ^b	9.954 ^b	0.116	0.001	0.452
Liver							
T-AOC (U/mg prot)	0.878 ^b	1.043 ^{a,b}	1.122 ^a	1.030 ^{a,b}	0.034	0.070	0.051
SOD (U/mg prot)	312.594	332.161	324.747	330.215	3.525	0.148	0.311
<i>GPX</i> (U/mg prot)	42.63 ^d	49.25 ^a	45.03 ^c	47.00 ^b	0.533	0.004	0.001
GSH (mg/g prot)	3.392 ^c	3.923 ^b	4.609 ^a	4.708 ^a	0.123	<0.001	0.194
CAT (U/mg prot)	10.434	10.542	10.774	11.018	0.151	0.159	0.825
MDA (nmol/mg prot)	1.258 ^a	1.029 ^b	1.011 ^b	1.026 ^b	0.025	<0.001	0.002

^{a-d}Means within the same row with no common superscript differ significantly ($P < 0.05$).

Abbreviations: CAT, catalase; GSH, glutathione; *GPX*, glutathione peroxidase; MDA, malonaldehyde; SOD, superoxide dismutase; T-AOC, total antioxidant capacity.

¹Standard error of the means ($n = 8$).

²Orthogonal polynomials were used to evaluate linear and quadratic responses to the levels of taurine treatment.

³CON, basal diet; TAU1, TAU2 and TAU3 group, basal diet adding 2.50, 5.00, and 7.50 g/kg TAU, respectively.

Table 5. Effects of different levels of taurine on serum and liver lipid metabolism in broilers.

Items	Dietary taurine concentration treatment ³				SEM ¹	P Value	
	CON	TAU1	TAU2	TAU3		Linear ²	Quadratic ²
Serum							
TC (mmol/L)	4.219 ^a	3.996 ^b	3.959 ^b	4.052 ^{a,b}	0.035	0.072	0.021
TG (mmol/L)	0.421 ^a	0.339 ^b	0.359 ^b	0.350 ^b	0.012	0.052	0.093
NEFA (u mol/L)	987.645	1,002.180	986.192	1,046.512	12.718	0.164	0.370
HDL-C (mmol/L)	3.127 ^b	3.429 ^{a,b}	3.617 ^a	3.412 ^{a,b}	0.067	0.070	0.051
LDL-C (mmol/L)	0.962	0.899	0.929	0.919	0.027	0.696	0.640
LPL (U/mL)	1.966	1.955	1.796	1.921	0.033	0.328	0.306
HL (U/mL)	2.826 ^a	2.283 ^b	2.212 ^b	2.228 ^b	0.055	<0.001	<0.001
TL (U/mL)	4.791 ^a	4.237 ^b	4.008 ^b	4.149 ^b	0.066	<0.001	<0.001
Liver							
TC (mmol/g prot)	0.099	0.093	0.093	0.103	0.004	0.767	0.368
TG (mmol/g prot)	3.017 ^a	2.478 ^{b,c}	2.289 ^c	2.760 ^{a,b}	0.085	0.150	0.002
NEFA (u mol/g prot)	103.142	100.165	91.958	100.194	3.118	0.554	0.386
LPL (U/mg prot)	1.330 ^b	1.505 ^a	1.461 ^{a,b}	1.530 ^a	0.032	0.022	0.828
HL (U/mg prot)	1.481	1.494	1.580	1.545	0.017	0.065	0.464
TL (U/mg prot)	2.811 ^b	2.999 ^{a,b}	3.041 ^{a,b}	3.075 ^a	0.039	0.008	0.606
ACC (pg/mg prot)	9.410	9.256	9.273	9.373	0.059	0.862	0.310
FAS (pg/mg prot)	582.583 ^a	559.667 ^b	563.208 ^{a,b}	561.958 ^{a,b}	3.824	0.054	0.147
HSL (pg/mg prot)	36.942 ^b	37.132 ^b	39.434 ^a	38.300 ^{a,b}	0.325	0.018	0.254

^{a-c}Means within the same row with no common superscript differ significantly ($P < 0.05$).

Abbreviations: ACC, acetyl CoA carboxylase; FAS, fatty acid synthase; HDL-C, high-density lipoprotein cholesterol; HL, hepatic lipase; HSL, hormone-sensitive triglyceride lipase; LDL-C, low-density lipoprotein cholesterol; LPL, lipoprotein lipase; NEFA, nonesterified fatty acid; TC, total cholesterol; TG, triglycerides; TL, total lipase.

¹Standard error of the means ($n = 8$).

²Orthogonal polynomials were used to evaluate linear and quadratic responses to the levels of taurine treatment.

³CON, basal diet; TAU1, TAU2 and TAU3 group, basal diet adding 2.50, 5.00, and 7.50 g/kg TAU, respectively.

Gene Expression Levels of Lipid Metabolism

As seen in Table 7, compared with the CON group, the mRNA expression levels of *AMPK α* , *SIRT1*, and *CPT-1* were increased ($P < 0.05$) and the mRNA expression level of *SREBP-1* was decreased in the TAU2 group. Apolipoprotein A1 (*APOA1*) mRNA expression was significantly increased by taurine supplementation ($P < 0.05$). Compared with the CON group, the mRNA expression of *PPAR α* was significantly increased ($P < 0.05$) except in the TAU1 group, whereas *FAS* expression was significantly decreased in the TAU1 group. However, the mRNA expression of *ACC* was not affected by taurine supplementation ($P > 0.05$).

DISCUSSION

Numerous studies have shown that dietary taurine supplementation increased the feed efficiency in the first wk (Tuftt and Jensen, 1992), enhanced ADG, decreased feed-to-gain ratio (Zeng et al., 2009), and improved growth performance of broiler chickens (Lee et al., 2004a). The aforementioned results were similar to our results that 0.5% taurine supplementation could increase the G/F and FI during the entire experimental period and increase the BWG in the starter phase and the entire experimental period. Taurine supplementation in ducks was accompanied with a significant increase of ADG and a decline of feed-to-gain ratio (Yang, 2011). Besides,

Table 6. Effects of dietary taurine supplementation on the expression levels of hepatic antioxidant-related genes of broilers.

Items ⁴	Dietary taurine concentration treatment ³				SEM ¹	P Value	
	CON	TAU1	TAU2	TAU3		Linear ²	Quadratic ²
<i>NRF2</i>	1.000 ^b	1.358 ^{a,b}	1.461 ^a	1.322 ^{a,b}	0.069	0.074	0.064
<i>HO-1</i>	1.000 ^b	1.321 ^{a,b}	1.634 ^a	1.608 ^a	0.094	0.010	0.323
<i>GPX</i>	1.000 ^b	1.640 ^{a,b}	1.807 ^a	1.165 ^{a,b}	0.126	0.530	0.010
<i>SOD1</i>	1.000	0.989	1.009	0.976	0.051	0.912	0.919
<i>CAT</i>	1.000	0.839	0.949	1.030	0.060	0.720	0.338

^{a,b}Means within the same row with no common superscript differ significantly ($P < 0.05$).

Abbreviations: *CAT*, catalase; *GPX*, glutathione peroxidase; *HO-1*, heme oxygenase-1; *NRF2*, nuclear factor erythroid 2-related factor 2; *SOD1*, superoxide dismutase 1.

¹Standard error of the means ($n = 8$).

²Orthogonal polynomials were used to evaluate linear and quadratic responses to the levels of taurine treatment.

³CON, basal diet; TAU1, TAU2 and TAU3 group, basal diet adding 2.50, 5.00, and 7.50 g/kg TAU, respectively.

⁴Expressed in arbitrary units. The expression of each target gene for the CON group was assigned a value of 1 and normalized against beta actin.

Table 7. Effects of dietary taurine supplementation on the expression levels of hepatic lipid metabolism-related genes of broilers.

Items ⁴	Dietary taurine concentration treatment ³				SEM ¹	P Value	
	CON	TAU1	TAU2	TAU3		Linear ²	Quadratic ²
<i>AMPKα</i>	1.000 ^b	1.681 ^{a,b}	2.097 ^a	1.780 ^{a,b}	0.179	0.085	0.159
<i>SIRT1</i>	1.000 ^b	1.629 ^{a,b}	1.876 ^a	1.435 ^{a,b}	0.116	0.112	0.017
<i>CPT-1</i>	1.000 ^b	1.467 ^{a,b}	1.630 ^a	1.257 ^{a,b}	0.098	0.271	0.032
<i>PPARα</i>	1.000 ^b	1.224 ^{a,b}	1.422 ^a	1.437 ^a	0.068	0.012	0.415
<i>APOA1</i>	1.000 ^b	1.733 ^a	1.695 ^a	1.689 ^a	0.107	0.027	0.050
<i>SREBP-1</i>	1.000 ^a	0.834 ^{a,b}	0.752 ^b	0.834 ^{a,b}	0.034	0.045	0.055
<i>FAS</i>	1.000 ^a	0.669 ^b	0.799 ^{a,b}	0.768 ^{a,b}	0.046	0.149	0.089
<i>ACC</i>	1.000	0.856	0.821	0.857	0.091	0.592	0.640

^{a,b}Means within the same row with no common superscript differ significantly ($P < 0.05$).

Abbreviations: *ACC*, acetyl-CoA carboxylase; *AMPKα*, adenosine monophosphate-activated protein kinase alpha; *APOA1*, apolipoprotein A1; *CPT-1*, carnitine palmitoyl-transferase 1; *FAS*, fatty acid synthase; *PPARα*, peroxisome proliferator-activated receptor α ; *SIRT1*, silent 1; *SREBP-1*, sterol regulatory element-binding protein-1.

¹Standard error of the means ($n = 8$).

²Orthogonal polynomials were used to evaluate linear and quadratic responses to the levels of taurine treatment.

³CON, basal diet; TAU1, TAU2 and TAU3 group, basal diet adding 2.50, 5.00, and 7.50 g/kg TAU, respectively.

⁴Expressed in arbitrary units. The expression of each target gene for the CON group was assigned a value of 1 and normalized against beta actin.

taurine was also used as a feed supplement to confer better growth and health of common carp fry (Abdel-Tawwab and Monier, 2018). Taurine improved the growth performance of broilers, which mainly benefited from its contribution to the increase palatability of feed and stimulate appetite (Koven et al., 2016). However, research on the effects of taurine supplementation on the growth performance in broilers was controversial. Yuan and Wang (2010) reported that taurine supplementation had no significant effect on the growth performance of broilers. We speculated that the reasons for these phenomena may be related to the type of diet, growth stage, feeding environment, and amount of taurine addition. In addition, our broiler chicks had low hatching weight; several studies have shown that broilers with lower hatching weight chicks had less BWG than heavy chicks when both were fed the control diets (Sklan et al., 2003; Wen et al., 2014), which could explain why the rate of growth/BWG of broilers is much slower in than it should be in this study. Moreover, stocking density (Li et al., 2019), protein source, and dietary structure (Qaisrani et al., 2014) would also affect the rate of growth of broilers.

Antioxidant activity is one of the most important biological functions of taurine (Cassol et al., 2010; Roy and Sil, 2012). Lipid peroxidation is one of the consequences of oxidative stress in biological systems (Eghbal et al., 2004). The removal of lipid peroxides mainly depends on nonenzymatic compounds such as GSH, and several important antioxidant enzymes such as SOD, CAT, and *GPX* (Rhee et al., 2013). The GSH is the main endogenous nonenzymatic antioxidant and could abolish lipid peroxides through a reaction catalyzed by *GPX* (Fang et al., 2002). The MDA content is a main degradation product of lipid peroxidation and associated with the oxidative damage. The lower MDA content indicated the lower reaction of lipid peroxidation (Ding et al., 2017). In this study, we found that dietary taurine

supplementation was conducive to the decline of MDA in the liver and serum of broilers, which could be ascribed to the enhancement of activities of GSH and *GPX*. Consistent with our results, numerous studies have confirmed that taurine supplementation significantly improved *GPX* activity, inhibited the accumulation of hydroxyl radicals, and then reduced lipid peroxidation (Winiarska et al., 2009; Yang et al., 2010). A similar result was obtained from the recent work, which suggested that the protective effects of taurine to alleviate oxidant damage via decreasing the MDA content (Huang et al., 2014). The activities of antioxidant enzymes are related to their gene transcription. Thus, we examined several key antioxidant gene expressions involved in antioxidant signals in the present study. Nuclear factor erythroid 2-related factor 2 is present in the cytosol under normal conditions, and when oxidative stress occurs, NRF2 is translocated into the nucleus and binds to the antioxidant response element to augment the expression of antioxidant genes (Li and Kong, 2009). Heme oxygenase-1 catalyzes the first and rate-limiting step in heme catabolism and plays an important role in reducing the total production of reactive oxygen species (Choi and Alam, 1996). The results showed that dietary taurine supplementation increased the genes expression of *NRF2*, *GPX*, and *HO-1* in the liver. We inferred that taurine, as an antioxidant, may improve the antioxidant properties of broilers by enhancing the radical scavenging capacity, reducing the lipid per-oxidation damage, blocking the gene expression of the oxidant stress-mediated induction and regulating the signaling pathway of NRF2. Similar to our data, Agca et al. (2014) reported that taurine supplementation enhanced the expression of *HO-1* through activating the *NRF2* and prompting it to translocate into the nucleus under stress. However, the detail way by which taurine regulates these signaling molecule expressions still needs to be elucidated.

It is well known that high blood TG, TC, and low-density lipoprotein cholesterol and low HDL-C are the major risk factors for cardiovascular and cerebrovascular disease (Glass and Witztum, 2001). The HDL-C is involved in the translocation of lipids from peripheral tissues to the liver for catabolism (Mooradian and Haas, 2014). The LPL catalyzes the hydrolysis in circulating chylomicrons, thus supplying NEFA for tissue utilization. The liver can absorb LPL and HL from the blood (Merkel et al., 1998), and the amount of these enzymes in the liver represents their status in the blood. Hormone-sensitive triglyceride lipase is a key enzyme in fat breakdown, thereby leading to a higher concentration of NEFA in serum through accelerating hydrolysis of TG to glycerol and fatty acid (Mersmann, 1998). The present study showed that dietary taurine supplementation decreased the level of TG in the serum and the liver, while exerting no influence on the concentration of NEFA, increased the activities of TL and HL in serum as well as LPL, TL, and HSL in the liver, and decreased the activity of FAS in the liver. The elevated HDL-C level in serum and the increased HSL activity in the liver confirmed a reduction of lipid accumulation and implied an alleviation of cardiovascular risk in broilers with taurine supplementation. Goodbridge (1973) and Lu et al. (2019) pointed out that taurine supplementation regulated the synthesis of fatty acids and promoted the activities of LPL and TL, and future facilitated the efficient utilization of NEFA in broilers, which could explain why the taurine supplementation had no influence on the NEFA in the serum and liver of broilers. Dong et al. (2015) found that carnitine could improve TG hydrolysis by improving LPL activity. Davail et al. (2000) showed that the LPL activity decreased, which could increase the TG level in serum of geese and even cause excessive fat deposition in the liver. This seems to suggest that taurine might cause the decrease of serum TG by enhancing the LPL activity in the liver and increase HDL-C level by decreasing the HL activity in serum (Zhou et al., 2015). Apolipoprotein A1 is the structural protein of HDL-C and plays a crucial role in the HDL-C assembly process as well as in the regulation of cholesterol homeostasis in broilers. We further measured the mRNA expression level of *APOA1* in broilers and found that the taurine supplementation improved the *APOA1* mRNA expression. Thus, the result indicated that dietary taurine supplementation upregulated the hepatic mRNA expression of *APOA1* and further increased the level of HDL-C in serum (Zhou et al., 2015). Meanwhile, the increased mRNA expression of *APOA1* also validated the serum TC reduction in broilers (Pirany et al., 2020).

The liver is the crucial organ for lipid metabolism including lipogenesis and fatty acid oxidation. The SREBP-1 plays an essential role in the regulation of lipogenesis involved in fatty acid and TG synthesis (Brown and Goldstein, 1997; Shimano et al., 1999; Aggarwal, 2010). Besides, SREBP-1 can further catalyze the transcription of the crucial genes, such as *ACC* and *FAS*, that are required in the fat synthesis (Demeure et al.,

2009). The content of FAS in tissues determines the maximum ability of de novo synthesis of fatty acids in tissues (Zhao et al., 2010), directly activated by SREBP-1. In the present study, taurine decreased the expression levels of *SREBP-1* and *FAS*, which proved that taurine supplementation reduced lipid synthesis to some extent. Besides, taurine significantly decreased the expression level of *PPAR α* in the liver. The *PPAR α* is a key factor in lipid metabolism and can enhance the body's fatty acid decomposition ability (Bremer, 2001) and diminish circulating TG and increase HDL-C level (Berger et al., 2005). The *PPAR α* as ligand-activated nuclear receptor participates in the transcriptional regulation of lipid metabolism and hepatic fatty acid oxidation. Previous investigations showed that the taurine supplementation enhanced the expression levels of *PPAR α* and carnitine palmitoyltransferase 1 (*CPT-1*), which in turn decreased the expression levels of *ACC*, *FAS*, and *SREBP-1*. Thus, the blood lipid was improved, and the fat deposition was reduced (Fouad et al., 2013; Lu et al., 2014; Han et al., 2016; Murakami, 2017), which suggested that dietary taurine supplementation might protect mitochondria and enhance lipid aerobic metabolism in the liver. Another observation in this study was that the expression levels of *AMPK α* , *SIRT1*, and *CPT-1* were all increased by 0.5% taurine supplementation. The *CPT-1* plays an important role in the decomposition of fatty acids. Fang et al. (2014) indicated that when the body used liver substrates to provide energy for the oxidation of beta, which would activate SIRT1 and upregulate the gene expression of *CPT-1*. It had been demonstrated that the activation of AMPK alleviated the decomposition and nuclear translocation of SREBP-1 (You et al., 2004) and reduced the expression levels of *ACC-1* and *FAS*, further inhibition of fatty acid synthesis pathway (Wang et al., 2018a; Wang et al., 2018b) and reduction of TC and TG contents in serum (Huang et al., 2013). These results revealed that taurine may ameliorate hepatic lipid accumulation by activating the signaling pathway of AMPK/SIRT1, which could decrease the expression of lipogenesis genes *SREBP-1* and *FAS* and increase the expression of fatty acid β -oxidation genes, including *PPAR α* and *CPT-1*. In addition, the synthesis and decomposition of lipid can be affected by heredity (Bouchard and Perusse, 1988), nutritional state (Saadoun and Leclercq, 1987) and environmental stimuli (Cao et al., 2011). The specific regulation mechanism of taurine on lipid metabolism remains to be further investigated in broilers.

CONCLUSION

We found that dietary taurine supplementation enhanced the growth performance and antioxidant function of broilers. We also discovered that dietary taurine supplementation regulated lipid accumulation of broilers may be owing to the activation of the AMPK/SIRT1 signal pathway, followed by the regulated expression of lipid metabolism-related genes. Together, this

experiment could provide references for taurine to relieve oxidative stress and lipid-related metabolic disorder.

ACKNOWLEDGMENTS

This research was financially supported by The National Experimental Teaching Demonstration Center of Animal Science.

Conflict of Interest Statement: The authors did not provide a conflict of interest statement.

REFERENCES

- Abdel-Tawwab, M., and M. N. Monier. 2018. Stimulatory effect of dietary taurine on growth performance, digestive enzymes activity, antioxidant capacity, and tolerance of common carp, *Cyprinus carpio* L., fry to salinity stress. *J. Fish Physiol. Biochem.* 44:639–649.
- Agca, C. A., M. Tuzcu, A. Hayirli, and K. Sahin. 2014. Taurine ameliorates neuropathy via regulating NF- κ B and Nrf2/HO-1 signaling cascades in diabetic rats. *Food Chem. Toxicol.* 71:116–121.
- Aggarwal, B. B. 2010. Targeting inflammation-induced obesity and metabolic diseases by curcumin and other nutraceuticals. *Annu. Rev. Nutr.* 30:173–199.
- Bandyopadhyay, G. K., M. Lu, E. Avolio, J. A. Siddiqui, J. R. Gayen, J. Wollam, C. U. Vu, N. W. Chi, D. T. O'Connor, and S. K. Mahata. 2015. Pancreastatin-dependent inflammatory signaling mediates obesity-induced insulin resistance. *Diabetes* 64:104–116.
- Berger, J. P., T. E. Akiyama, and P. T. Meinke. 2005. PPARs: therapeutic targets for metabolic disease. *Trends Pharmacol. Sci.* 26:244–251.
- Bonfleur, M. L., P. C. Borck, R. A. Ribeiro, L. C. Caetano, G. M. Soares, E. M. Carneiro, and S. L. Balbo. 2015. Improvement in the expression of hepatic genes involved in fatty acid metabolism in obese rats supplemented with taurine. *Life Sci.* 135:15–21.
- Bouchard, C., and L. Pérusse. 1988. Heredity and body fat. *Annu. Rev. Nutr.* 8:259–277.
- Bremer, J. 2001. The biochemistry of hypo- and hyperlipidemic fatty acid derivatives: metabolism and metabolic effects. *Prog. Lipid Res.* 40:231–268.
- Brown, M. S., and J. L. Goldstein. 1997. The SREBP pathway: regulation of cholesterol metabolism by proteolysis of a membrane-bound transcription factor. *Cell* 89:331–340.
- Cantó, C., Z. Gerhart-Hines, J. N. Feige, M. Lagouge, L. Noriega, J. C. Milne, P. J. Elliott, P. Puigserver, and J. Auwerx. 2009. AMPK regulates energy expenditure by modulating NAD⁺ metabolism and SIRT1 activity. *Nature* 458:1056–1060.
- Cao, L., E. Y. Choi, X. L. Liu, A. Martin, C. Wang, X. Xu, and M. J. During. 2011. White to brown fat phenotypic switch induced by genetic and environmental activation of a hypothalamic-adipocyte axis. *Cell Metab* 14:324–338.
- Cassol, Jr, O.J., G. T. Rezin, F. C. Petronilho, G. Scaini, C. L. Goncalves, G. K. Ferreira, R. Roesler, G. Schwartzmann, F. Dal-Pizzol, and E. L. Streck. 2010. Effects of N-acetylcysteine/deferaxamine, taurine and RC-3095 on respiratory chain complexes and creatine kinase activities in rat brain after sepsis. *Neurochem. Res.* 35:515–521.
- Chang, Y. Y., C. H. Chou, C. H. Chiu, K. T. Yang, Y. L. Lin, W. L. Weng, and Y. C. Chen. 2011. Preventive effects of taurine on development of hepatic steatosis induced by a high-fat/cholesterol dietary habit. *J. Agric. Food Chem.* 59:450–457.
- Chen, X. C., B. M. Sebastian, H. Tang, M. M. McMullen, A. Axhemi, D. W. Jacobsen, and L. E. Nagy. 2009. Taurine supplementation prevents ethanol-induced decrease in serum adiponectin and reduces hepatic steatosis in rats. *Hepatology* 49:1554–1562.
- Choi, A. M., and J. Alam. 1996. Heme oxygenase-1: function, regulation, and implication of a novel stress-inducible protein in oxidant-induced lung injury. *Am. J. Respir. Cell Mol. Biol.* 15:9–19.
- Chu, Y., R. L. Gómez, P. Huang, Z. Wang, Y. Xu, X. Yao, M. Bao, J. Yan, H. Song, and G. Wang. 2014. Liver Med23 ablation improves glucose and lipid metabolism through modulating FOXO1 activity. *Cell Res.* 24:1250–1265.
- Chung, S. S., M. Kim, B. S. Youn, N. S. Lee, J. W. Park, I. K. Lee, Y. S. Lee, J. B. Kim, Y. M. Cho, H. K. Lee, and K. S. Park. 2009. Glutathione peroxidase 3 mediates the antioxidant effect of peroxisome proliferator-activated receptor gamma in human skeletal muscle cells. *Mol. Cell Biol.* 29:20–30.
- Colak, Y., A. Yesil, H. H. Mutlu, O. T. Caklili, C. Ulasoglu, E. Senates, M. Takir, O. Kostek, Y. Yilmaz, Enc. F. Yilmaz, G. Tasan, and I. Tuncer. 2014. A potential treatment of non-alcoholic fatty liver disease with SIRT1 activators. *J. Gastrointest. Liver Dis.* 23:311–319.
- Das, J., V. Vasan, and P. C. Sil. 2012. Taurine exerts hypoglycemic effect in alloxan-induced diabetic rats, improves insulin-mediated glucose transport signaling pathway in heart and ameliorates cardiac oxidative stress and apoptosis. *Toxicol. Appl. Pharmacol.* 258:296–308.
- Davail, S., G. Guy, J. M. Andre, D. Hermier, and R. Hoo-Paris. 2000. Metabolism in two breeds of geese with moderate or large overfeeding induced liver-steatosis. *Comp. Biochem. Physiol. A. Mol. Integr. Physiol.* 126:91–99.
- Demeure, O., C. Duby, C. Desert, S. Assaf, D. Hazard, H. Guillou, and S. Lagarrigue. 2009. Liver X receptor alpha regulates fatty acid synthase expression in chicken. *Poult. Sci.* 88:2628–2635.
- Department of Agriculture. 2016. Pages 2483–2485 in Determination of Taurine in Feeds-High Performance Liquid Chromatography.
- Ding, X., C. W. Yang, and Z. B. Yang. 2017. Effects of star anise (*Illicium verum* Hook. F.), essential oil, and leavings on growth performance, serum, and liver antioxidant status of broiler chickens. *J. Appl. Poult. Res.* 26:459–466.
- Dong, J., L. Li, Y. H. Yu, Y. Y. Zhao, Y. K. Chen, Q. B. Wang, Q. J. Wang, and D. M. Zhang. 2015. Effects of exogenous carnitine on growth performance and biochemical indexes of common carp (*Cyprinus carpio*) juvenile. *J. Northwest A&F Univ. (Nat Sci Ed)*. 43:58–64 (in Chinese).
- Dreger, H., K. Westphal, N. Wilck, G. Baumann, V. Stangl, K. Stangl, and S. Meiners. 2010. Protection of vascular cells from oxidative stress by proteasome inhibition depends on Nrf2. *Cardiovasc. Res.* 85:395–403.
- Eghbal, M., P. Pennefather, and P. O'Brien. 2004. H2S cytotoxicity mechanism involves reactive oxygen species formation and mitochondrial depolarisation. *Toxicology* 203:69–76.
- Elwahab, A. H. A., B. K. Ramadan, M. F. Schaal, and A. M. Tolba. 2017. A novel role of SIRT1/FGF-21 in taurine protection against cafeteria diet-induced steatohepatitis in rats. *Cell Physiol. Biochem.* 43:644–659.
- Fang, X. L., X. T. Zhu, S. F. Chen, Z. Q. Zhang, Q. J. Zeng, L. Deng, J. L. Peng, J. J. Yu, L. N. Wang, S. B. Wang, P. Gao, Q. Y. Jiang, and G. Shu. 2014. Differential gene expression pattern in hypothalamus of chickens during fasting-induced metabolic reprogramming: functions of glucose and lipid metabolism in the feed intake of chickens. *Poult. Sci.* 93:2841–2854.
- Fang, Y. Z., S. Yang, and G. J. N. Wu. 2002. Free radicals, antioxidants, and nutrition. *Nutrition* 18:872–879.
- Fellenberg, M. A., and H. Speisky. 2006. Antioxidants: their effects on broiler oxidative stress and its meat oxidative stability. *Worlds Poult. Sci. J.* 62:53–70.
- Fouad, A. M., H. K. El-Senousey, X. J. Yang, and J. H. Yao. 2013. Dietary L-arginine supplementation reduces abdominal fat content by modulating lipid metabolism in broiler chickens. *Animal* 7:1239–1245.
- Furukawa, S., T. Fujita, M. Shimabukuro, M. Iwaki, Y. Yamada, Y. Nakajima, O. Nakayama, M. Makishima, M. Matsuda, and I. Shimomura. 2004. Increased oxidative stress in obesity and its impact on metabolic syndrome. *J. Clin. Invest.* 114:1752–1761.
- Ge, X. K., A. A. Wang, Z. X. Ying, L. G. Zhang, W. P. Su, K. Cheng, C. C. Feng, Y. M. Zhou, L. L. Zhang, and T. Wang. 2019. Effects of diets with different energy and bile acids levels on growth performance and lipid metabolism in broilers. *Poult. Sci.* 98:887–895.
- Gentile, C. L., A. M. Nivala, J. C. Gonzales, K. T. Pfaffenbach, D. Wang, Y. R. Wei, H. Jiang, D. J. Orlicky, D. R. Petersen, M. J. Pagliassotti, and K. N. Maclean. 2011. Experimental evidence for therapeutic potential of taurine in the treatment of nonalcoholic fatty liver disease. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 301:R1710–R1722.
- Glass, C. K., and J. L. Witztum. 2001. Atherosclerosis. The road ahead. *Cell* 104:503–516.

- Goodbridge, A. G. 1973. On the relationship between fatty acid synthesis and the total activities of acetyl coenzyme A carboxylase and fatty acid synthetase in the liver of prenatal and early postnatal chicks. *J. Biol. Chem.* 248:1932–1938.
- Griffin, H. D., K. Guo, D. Windsor, and S. C. Butterwith. 1992. Adipose tissue lipogenesis and fat deposition in leaner broiler chickens. *J. Nutr.* 122:363–368.
- Guo, Y. Y., B. Y. Li, W. Q. Peng, L. Guo, and Q. Q. Tang. 2019. Taurine-mediated browning of white adipose tissue is involved in its anti-obesity effect in mice. *J. Biol. Chem.* 294:15014–15024.
- Han, J., L. L. Li, D. Wang, and H. T. Ma. 2016. (-)-Hydroxycitric acid reduced fat deposition via regulating lipid metabolism-related gene expression in broiler chickens. *Lipids Health Dis.* 15:37.
- Hou, W. L., J. Yin, M. Alimujiang, X. Y. Yu, L. G. Ai, Y. Q. Bao, F. Liu, and W. P. Jia. 2018. Inhibition of mitochondrial complex I improves glucose metabolism independently of AMPK activation. *J. Cell. Mol. Med.* 22:1316–1328.
- Huang, J., S. K. Das, P. Jha, W. Al Zoughbi, S. Schauer, T. Claudel, V. Sexl, P. Vesely, R. Birner-Gruenberger, D. Kratky, M. Trauner, and G. Hoeffler. 2013. The PPAR α agonist fenofibrate suppresses B-cell lymphoma in mice by modulating lipid metabolism. *Biochim. Biophys. Acta.* 1831:1555–1565.
- Huang, C. X., B. Wang, Z. Min, and J. Yuan. 2014. Dietary inclusion level and time effects of taurine on broiler performance, meat quality, oxidative status and muscle taurine content. *Br. Poult. Sci.* 55:598–604.
- Huxtable, R. J. 1992. Physiological actions of taurine. *Physiol. Rev.* 72:101–163.
- Kim, H. J., and N. D. Vaziri. 2010. Contribution of impaired Nrf2-Keap1 pathway to oxidative stress and inflammation in chronic renal failure. *Am. J. Physiol.-renal. Physiol.* 298:F662–F671.
- Kleinhenz, J. M., D. J. Kleinhenz, S. J. You, J. D. Ritzenthaler, J. M. Hansen, D. R. Archer, R. L. Sutliff, and C. M. Hart. 2009. Disruption of endothelial peroxisome proliferator-activated receptor-gamma reduces vascular nitric oxide production. *Am. J. Physiol. Heart Circul. Physiol.* 297:H1647–H1654.
- Koven, W., A. Peduel, M. Gada, O. Nixon, and M. Ucko. 2016. Taurine improves the performance of white grouper juveniles (*epinephelus aeneus*) fed a reduced fish meal diet. *Aquaculture* 460:8–14.
- Lee, D. N., Y. H. Cheng, Y. S. Chuang, J. L. Shive, Y. M. Lian, H. W. Wei, and C. F. Weng. 2004. Effects of dietary taurine supplementation on growth performance, serum constituents and antibody production of broilers. *Asian Austral J. Anim. Sci.* 17:109–115.
- Li, W., and A. N. Kong. 2009. Molecular mechanisms of Nrf2-mediated antioxidant response. *Mol. Carcinog.* 48:91–104.
- Li, M., H. Lai, Q. Li, S. Y. Gong, and R. X. Wang. 2016. Effects of dietary taurine on growth, immunity and hyperammonemia in juvenile yellow catfish *pelteobagrus fulvidraco* fed all-plant protein diets. *Aquaculture* 450:349–355.
- Li, X. M., M. H. Zhang, S. M. Liu, J. H. Feng, D. D. Ma, Q. X. Liu, Y. Zhou, X. J. Wang, and S. Xing. 2019. Effects of stocking density on growth performance, growth regulatory factors, and endocrine hormones in broilers under appropriate environments. *Poult. Sci.* 98:6611–6617.
- Livak, K. J., and T. D. Schmittgen. 2001. Analysis of relative gene expression data using real-time quantitative PCR and the 2⁻(Delta Delta C(T)) method. *Methods* 25:402–408.
- Lu, Z., X. F. He, B. B. Ma, L. Zhang, J. L. Li, Y. Jiang, G. H. Zhou, and F. Gao. 2019. Dietary taurine supplementation decreases fat synthesis by suppressing the liver X receptor alpha pathway and alleviates lipid accumulation in the liver of chronic heat-stressed broilers. *J. Sci. Food Agr.* 99:5631–5637.
- Lu, Y. L., W. Jing, L. S. Feng, L. Zhang, J. F. Xu, T. J. You, and J. Zhao. 2014. Effects of hypoxic exercise training on microRNA expression and lipid metabolism in obese rat livers. *J. Zhejiang Univ. Sci. B.* 15:820–829.
- Merkel, M., P. H. Weinstock, T. Chajek-Shaul, H. Radner, B. Y. Yin, J. L. Breslow, and I. J. Goldberg. 1998. Lipoprotein lipase expression exclusively in liver. A mouse model for metabolism in the neonatal period and during cachexia. *J. Clin. Invest.* 102:893–901.
- Mersmann, H. J. 1998. Lipoprotein and hormone-sensitive lipases in porcine adipose tissue. *J. Anim. Sci.* 76:1396–1404.
- Mooradian, A. D., and M. J. Haas. 2014. The effect of nutritional supplements on serum high-density lipoprotein cholesterol and apolipoprotein A-I. *Am. J. Cardiovasc. Drugs* 14:253–274.
- Motohashi, H., and M. Yamamoto. 2004. Nrf2-Keap1 defines a physiologically important stress response mechanism. *Trends Mol. Med.* 10:549–557.
- Murakami, S. 2015. Role of taurine in the pathogenesis of obesity. *Mol. Nutr. Food Res.* 59:1353–1363.
- Murakami, S. 2017. The physiological and pathophysiological roles of taurine in adipose tissue in relation to obesity. *Life Sci.* 186:80–86.
- Nardelli, T. R., R. A. Ribeiro, S. L. Balbo, E. C. Vanzela, E. M. Carneiro, A. C. Boschero, and M. L. Bonfleur. 2011. Taurine prevents fat deposition and ameliorates plasma lipid profile in monosodium glutamate-obese rats. *Amino Acids* 41:901–908.
- Palomer, X., L. Salvado, E. Barroso, and M. Vazquez-Carrera. 2013. An overview of the crosstalk between inflammatory processes and metabolic dysregulation during diabetic cardiomyopathy. *Int. J. Cardiol.* 168:3160–3172.
- Pirany, N., A. Bakrani Balani, H. Hassanpour, and H. Mehraban. 2020. Differential expression of genes implicated in liver lipid metabolism in broiler chickens differing in weight. *Br. Poult. Sci.* 61:1466–1799.
- Qaisrani, S. N., P. C. Moquet, M. M. van Krimpen, R. P. Kwakkel, M. W. Versteegen, and W. H. Hendriks. 2014. Protein source and dietary structure influence growth performance, gut morphology, and hindgut fermentation characteristics in broilers. *Poult. Sci.* 93:3053–3064.
- Rhee, J. S., I. T. Yu, B. M. Kim, C. B. Jeong, K. W. Lee, M. J. Kim, S. J. Lee, G. S. Park, and J. S. Lee. 2013. Copper induces apoptotic cell death through reactive oxygen species-triggered oxidative stress in the intertidal copepod *tigriopus japonicus*. *Aquat. Toxicol.* 132:182–189.
- Roy, A., and P. C. Sil. 2012. Tertiary butyl hydroperoxide induced oxidative damage in mice erythrocytes: protection by taurine. *Pathophysiology* 19:137–148.
- Ruderman, N. B., X. J. Xu, L. Nelson, J. M. Cacicedo, A. K. Saha, F. Lan, and Y. Ido. 2010. AMPK and SIRT1: a long-standing partnership? *Am. J. Physiol. Endocrinol. Metab.* 298:E751–E760.
- Saadoun, A., and B. Leclercq. 1987. In vivo lipogenesis of genetically lean and fat chickens-effects of nutritional state and dietary-fat. *J. Nutr.* 117:428–435.
- Shimano, H., N. Yahagi, M. Amemiya-Kudo, A. H. Hastay, J. Osuga, Y. Tamura, F. Shionoiri, Y. Iizuka, K. Ohashi, K. Harada, T. Gotoda, S. Ishibashi, and N. Yamada. 1999. Sterol regulatory element-binding protein-1 as a key transcription factor for nutritional induction of lipogenic enzyme genes. *J. Biol. Chem.* 274:35832–35839.
- Singh, A., T. Rangasamy, R. K. Thimmulappa, H. Lee, W. O. Osburn, R. Brigelius-Flohe, T. W. Kensler, M. Yamamoto, and S. Biswal. 2006. Glutathione peroxidase 2, the major cigarette smoke-inducible isoform of GPX in lungs, is regulated by Nrf2. *Am. J. Respir. Cell Mol. Biol.* 35:639–650.
- Sklan, D., S. Heifetz, and O. Halevy. 2003. Heavier chicks at hatch improves marketing body weight by enhancing skeletal muscle growth. *Poult. Sci.* 82:1778–1786.
- Tessari, P., A. Coracina, A. Cosma, and A. Tiengo. 2009. Hepatic lipid metabolism and non-alcoholic fatty liver disease. *Nutr. Metab. Cardiovasc. Dis.* 19:291–302.
- Tian, D. L., R. J. Guo, Y. M. Li, P. P. Chen, B. B. Zi, J. J. Wang, R. F. Liu, Y. N. Min, Z. P. Wang, Z. Y. Niu, and F. Z. Liu. 2019. Effects of lysine deficiency or excess on growth and the expression of lipid metabolism genes in slow-growing broilers. *Poult. Sci.* 98:2927–2932.
- Tsuboyama-Kasaoka, N., C. Shozawa, K. Sano, Y. Kamei, S. Kasaoka, Y. Hosokawa, and O. Ezaki. 2006. Taurine (2-aminoethanesulfonic acid) deficiency creates a vicious circle promoting obesity. *Endocrinology* 147:3276–3284.
- Tufft, L. S., and L. S. Jensen. 1992. Influence of dietary taurine on performance and fat retention in broilers and Turkey poults fed varying levels of fat. *Poult. Sci.* 71:880–885.
- Wang, C., Y. Li, M. Hao, and W. Li. 2018a. Astragaloside IV inhibits triglyceride accumulation in insulin-resistant HepG2 cells via AMPK-induced SREBP-1c phosphorylation. *Front. Pharmacol.* 9:345.

- Wang, Q., S. Liu, A. Zhai, B. Zhang, and G. Tian. 2018b. AMPK-mediated regulation of lipid metabolism by phosphorylation. *Biol. Pharm. Bull.* 41:985–993.
- Wen, C., Y. P. Chen, P. Wu, T. Wang, and Y. M. Zhou. 2014. Mstn, mTOR and FoxO4 are involved in the enhancement of breast muscle growth by methionine in broilers with lower hatching weight. *PLoS ONE* 9:e114236.
- Winiarska, K., K. Szymanski, P. Gorniak, and M. Dudziak. 2009. Hypoglycaemic, antioxidative and nephroprotective effects of taurine in alloxan diabetic rabbits. *Biochimie* 91:261–270.
- Yang, S. F., B. S. Tzang, K. T. Yang, Y. C. Hsiao, Y. Y. Chang, C. H. Chan, S. G. Fu, and Y. C. Chen. 2010. Taurine alleviates dyslipidemia and liver damage induced by a high-fat/cholesterol-dietary habit. *Food Chem.* 120:156–162.
- Yang, X. R., A. Wang, and Z. J. Guo. 2011. Effects of taurine on growth performance, antioxidant function and immune organ development of caged egg-type ducklings. *Chin. J. Anim. Nutr.* 23:807–812 (in Chinese).
- You, M., M. Matsumoto, C. M. Pacold, W. K. Cho, and D. W. Crabb. 2004. The role of AMP-activated protein kinase in the action of ethanol in the liver. *Gastroenterology* 127:1798–1808.
- Yu, X., X. G. Shao, H. Sun, Y. N. Li, J. Yang, Y. C. Deng, and Y. G. Huang. 2008. Activation of cerebral peroxisome proliferator-activated receptors gamma exerts neuroprotection by inhibiting oxidative stress following pilocarpine-induced status epilepticus. *Brain Res.* 1200:146–158.
- Yuan, J. M., and Z. H. Wang. 2010. Effect of taurine on intestinal morphology and utilisation of soy oil in chickens. *Br. Poult. Sci.* 51:540–545.
- Zeng, D. S., Z. H. Gao, J. H. Zhao, X. L. Huang, L. Duo, and Y. Tian. 2009. Effects of taurine on growth performance, immune organ development and antioxidative ability of broilers. *Chin. J. Vet. Sci.* 29:774–778 (in Chinese).
- Zhang, X. H., X. Zhong, Y. M. Zhou, H. M. Du, and T. Wang. 2009. Effect of RRR-alpha-tocopherol succinate on the growth and immunity in broilers. *Poult. Sci.* 88:959–966.
- Zhao, S., H. Ma, S. Zou, W. Chen, and R. Zhao. 2010. Hepatic lipogenesis in broiler chickens with different fat deposition during embryonic development. *J. Vet. Med. A. Physiol. Pathol. Clin. Med.* 54:1–6.
- Zhou, L., C. Li, L. Gao, and A. Wang. 2015. High-density lipoprotein synthesis and metabolism (Review). *Mol. Med. Rep.* 12:4015–4021.