Effects of methylsulfonylmethane on growth performance, immunity, antioxidant capacity, and meat quality in Pekin ducks

H. L. Yan,[*] S. C. Cao,[*] Y. D. Hu,[§] H. F. Zhang,[†] and J. B. Liu[*,†,1]

*School of Life Science and Engineering, Southwest University of Science and Technology, Ya'an, Sichuan 621010, PR China; [†]State Key Laboratory of Animal Nutrition, Institute of Animal Sciences, Chinese Academy of Agricultural Sciences, Beijing 100193, PR China; and [§]Farm Animal Genetic Resources Exploration and Innovation Key Laboratory of Sichuan Province, Sichuan Agricultural University, Ya'an, Sichuan 625014, PR China

ABSTRACT This study was conducted to determine the effect of methylsulfonylmethane (**MSM**) on growth performance, immune function, antioxidant capacity, and meat quality in Pekin ducks. A total of 960 female 1-day-old Pekin ducklings (53.3 ± 0.4 g) were randomly allotted to 3 treatments with 8 replicates of 40 birds, based on their body weight (**BW**). The experiment lasted 6 wks, and dietary treatments included a corn–soybean meal–based diet supplemented with 0%, 0.15%, and 0.3% MSM, that is, CON, MSM1, and MSM2, respectively. Growth performance, serum profiles, and meat quality were determined. During the period of days 22–42, BW gain (**BWG**) in MSM2 treatment was higher ($P < 0.05$) and feed-to-gain ratio (F/G) was lower ($P < 0.05$) than those of CON and MSM1 treatments. BW gain and final BW in MSM2 treatment were increased ($P < 0.05$) compared with CON and MSM1 treatments during the period of days 1–42. Serum activities of superoxide dismutase and glutathione peroxidase, total antioxidative capacity, and concentrations of interleukin-2 and interleukin-6 were higher ($P < 0.05$) in MSM2 than in CON treatment. Ducks in the MSM2 treatment group had lower ($P < 0.05$) serum malondialdehyde, interferon gamma, and tumor necrosis factor-α levels than those in the CON treatment group. The supplementation of MSM increased ($P < 0.05$) water-holding capacity and redness (a*) and decreased ($P < 0.05$) values for 2-thiobarbituric acid and drip loss on day 5. Ducks in the MSM2 treatment group had higher ($P < 0.05$) pH_{24h} than those in the CON treatment group. Taken together, the inclusion of MSM (0.3%) increased final BW and BWG during periods of days 22–42 and days 1–42, reduced feed-to-gain ratio during the period of days 22–42, and resulted in positive effects on immunity, antioxidant capacity, and meat quality.

Key words: duck, methylsulfonylmethane, meat quality, performance

2020 Poultry Science 99:1069–1074
https://doi.org/10.1016/j.psj.2019.10.002

INTRODUCTION

Methylsulfonylmethane (**MSM**) is a natural source of organic dietary sulfur, widely popular as a supplement, and it has also been shown to ameliorate inflammation and oxidative stress induced by lipopolysaccharides in murine macrophages through increasing expression of proinflammatory mediators including nitric oxide, prostaglandins, and proinflammatory cytokines (Kim et al., 2009). There are several reports providing in vitro evidence of the antioxidant, anti-inflammatory, antibacterial, antifungal, and antiviral activity of MSM (Kim et al., 2006, 2014; Maranon et al., 2008; Amirshahrokhi et al., 2011), whereas there are a few in vivo studies that have evaluated its growth-promoting effect and its effect on meat quality of ducks.

Methylsulfonylmethane is present in some natural green plants, fruits, and vegetables, such as tomato, corn, and apple. As a dietary supplement, MSM could be used to treat or prevent osteoarthritis (Gregory et al., 2008), interstitial cystitis, parasites, constipation, musculoskeletal pain, and allergies (Childs, 1994; Parcell, 2002; Maranon et al., 2008). Several toxicity studies demonstrated that MSM is generally nontoxic to humans (reviewed by Parcell, 2002). The US Food and Drug Administration indicated that MSM is a natural source of sulfur that could be used as a joint health supplement (FDA, 2004). We hypothesized that MSM

Received May 13, 2019.
Accepted October 1, 2019.

[1]Corresponding author: liuswust@163.com

may exhibit positive effect on growth performance in ducks owing to its anti-inflammatory and antioxidant properties. A recent study also demonstrated that MSM showed beneficial effects on growth performance, excreta microbiota, and meat quality in broilers (Jiao et al., 2017). However, scarce information about the effect of MSM on ducks was available. Therefore, the objective of this study is to determine the impact of MSM on growth performance, immunity, antioxidant capacity, and meat quality in Pekin ducks.

MATERIALS AND METHODS

Experimental Design and Duck Husbandry

The Animal Welfare Committee of the Southwest University of Science and Technology approved the animal care protocol used for these experiments.

A total of 960 female Pekin ducklings at 1 D of age with an average initial body weight (**BW**) of 53.3 ± 0.4 g were blocked on the basis of BW and placed in stainless steel battery brooders. The cages were equipped with a feeder, a nipple drinker, and raised plastic floors. All birds were housed in an environmentally controlled facility. There were 3 treatments, each with 8 replications per treatment and 40 ducks per replication in a randomized complete block design in this 42-D trial. The dietary treatments included the following: (1) basal diet, CON; (2) basal diet containing 0.15% MSM, MSM1; and (3) basal diet containing 0.3% MSM, MSM2. A 2-phase feeding program was used: a starter diet from day 1 to 21 and a grower diet from day 22 to 42. All diets (Table 1) were formulated to meet or exceed the NRC (1994) requirements for ducks. Methylsulfonylmethane was added at the expense of corn. Diets were fed in the pellet form, and feed and water were provided *ad libitum* throughout the experiment. The temperature was kept at 33°C from 1 to 3 D of age, and then, it was reduced gradually to approximately 25°C until 14 D of age and was kept at approximately 16 to 22°C thereafter (Liu et al., 2019a).

Feed samples were analyzed for dry matter (Method 934.01), crude protein (Method 990.03), and total ash (Method 942.05) according to the standard procedures of the AOAC (2000). Calcium concentration was determined using an atomic absorption spectrophotometer (Varian'50, Varian, Palo Alto, CA), and the concentration of phosphorus was determined spectrophotometrically (NanoDrop 2000c, Thermo Scientific, MA) according to Liu et al. (2018), with some modifications. The amino acids of all diets were determined, after acid hydrolysis with 6 N HCl at 110°C for 24 h, using an amino acid analyzer (Biochrom 20, Pharmacia Biotech, Cambridge, England). Before acid hydrolysis, methionine and cystine were oxidized with formic acid.

Table 1. Diet composition (as-fed basis).

Items	Starter[1]	Grower[1]
Ingredients, %		
Corn	57.11	62.63
Soybean meal	36.63	31.13
Soybean oil	2.27	2.35
Monocalcium phosphate	1.33	1.29
Limestone	1.67	1.59
Sodium chloride	0.20	0.25
Choline chloride (60%)	0.10	0.10
DL-Methionine (99%)	0.17	0.16
L-lysine (78%)	0.02	-
Vitamin premix[2]	0.25	0.25
Trace mineral premix[3]	0.25	0.25
Analytical composition		
ME, kcal/kg[4]	2,950	3,020
Crude protein, %	20.48	18.50
Dry matter, %	87.4	87.3
Total ash, %	5.02	5.00
Lysine, %	1.18	1.03
Methionine, %	0.50	0.46
Methionine + cystine, %	0.83	0.77
Threonine, %	0.79	0.72
Ca, %	0.95	0.90
Available phosphorus, %	0.45	0.43

[1]Starter diets, provided during days 1–21; grower diets, provided during days 22–42.

[2]Provided per kg of diet: vitamin A (from retinyl acetate), 12,500 IU; cholecalciferol, 3,500 IU; vitamin E (from DL-α-tocopheryl acetate), 35 IU; vitamin B12, 0.06 mg; riboflavin, 5.4 mg; nicotinamide, 50 mg; calcium pantothenate, 35 mg; menadione (from menadione dimethylpyrimidinol), 2.5 mg; folic acid, 0.8 mg; thiamine, 3 mg; pyridoxine, 8 mg; biotin, 0.25 mg; choline (as choline chloride), 560 mg; ethoxyquin, 80 mg.

[3]Provided per kg of diet: Mn (from $MnSO_4.H_2O$), 80 mg; Zn (from ZnO), 65 mg; Fe (from $FeSO_4.7H_2O$), 50 mg; Cu (from $CuSO_4.5H_2O$), 8 mg; I (from $Ca(IO_3)_2.H_2O$), 1.8 mg; Se, 0.30 mg.

[4]Calculated values.

Sampling and Measurements

At 21 D and 42 D of age, body weight gain (**BWG**), feed intake (**FI**), and feed-to-gain ratio (**F/G**) of ducks from each cage were measured. Feed intake and F/G were corrected for mortality (Zhang et al., 2019).

At the end of the experiment, 8 birds from each replicate were randomly selected from each cage, and blood samples were collected from the jugular vein into a sterile syringe. The blood samples were then centrifuged at 3,000 × g for 15 min, and the serum was separated. The levels of superoxide dismutase (**SOD**), total antioxidative capacity (**T-AOC**), malondialdehyde (**MDA**), glutathione peroxidase (**GSH-PX**), immunoglobin G (**IgG**), interleukin-2 (**IL-2**), interleukin-6 (**IL-6**), tumor necrosis factor-α (**TNF-α**), and interferon gamma (**IFN-γ**) in the serum were analyzed using the ELISA method (Jiancheng Biotechnology Institute, Nanjing, China) by following the kit instructions (Liu et al., 2019b, Yan et al., 2019).

After blood collection, the same birds were individually weighed, electrically stunned, and then killed immediately by decapitation and eviscerated manually. The carcass weight (without the neck and feet), breast meat (including the pectoralis major and pectoralis minor), abdominal fat, liver, gizzard, pancreas, thymus, bursa of Fabricius, and spleen were all removed manually by the same trained person from carcasses. Then, they were weighed, and the percentages relative to live BW at processing were also calculated. The pH of the breast meat was measured 45 min and 24 h after postmortem using a calibrated, glass electrode pH meter

(WTW pH 340-A, WTH Measurement Systems Inc., Ft. Myers, FL). The breast meat lightness (L*), redness (a*), and yellowness (b*) values were determined (Minolta CR410 Chromameter; Konica Minolta Sensing Inc., Osaka, Japan). Drip loss was measured by using approximately 2 g of the meat sample according to the plastic bag method described by Honikel (1998). Cook loss was determined as described previously by Sullivan et al. (2007). The water-holding capacity (**WHC**) was measured in accordance with the methods described by Kauffman et al. (1986). The 2-thiobarbituric acid–reactive substances (**TBARS**) were measured by the method described by Witte et al. (1970). The TBARS values were expressed as milligrams of MDA per kilogram of muscle. Trichloroacetic acid solution (20% wt/vol) was used for the extraction. The chromium concentration was determined by spectrophotometry (UV-1201, Shimadzu, Kyoto, Japan).

Statistical Analysis

Data were analyzed by ANOVA using the GLM procedure of SAS (SAS Institute Inc., Cary, NC), with the cage being the experimental unit. The initial BW was used as a covariate for the BWG and ADG. Differences among all treatments were detected by Duncan's multiple range tests. Variability in the data is expressed as the standard error of mean. Probability values less than 0.05 were considered significant.

RESULTS

Growth Performance

During the period of days 1–21, there were no differences ($P > 0.05$) in BWG, FI, or F/G among treatments (Table 2). During the period of days 22–42, dietary supplementation with 0.3% MSM increased ($P < 0.05$) BWG compared with that of controls and decreased ($P < 0.05$) F/G of ducks compared with that of ducks in the CON and MSM1 treatment groups. During the entire experiment, BWG and final BW was increased ($P < 0.05$) in the MSM2 treatment group compared with the CON and MSM1 treatment groups.

Blood Profiles

Birds in the MSM2 treatment group had higher ($P < 0.05$) serum activities of SOD, GSH-PX, and T-AOC, higher ($P < 0.05$) serum levels of IL-2 and IL-6, and lower ($P < 0.05$) serum MDA concentration than those in the CON treatment group (Table 3). Serum IFN-γ and TNF-α concentrations were lower ($P < 0.05$) in the MSM2 treatment group than in the CON and MSM1 treatment groups. No differences were observed ($P > 0.05$) in the serum IgG level among the treatments.

Table 2. Effects of MSM on growth performance in Pekin ducks.[1]

Item[2]	CON[3]	MSM1[3]	MSM2[3]	SEM[4]	*P*-value
Initial BW, g	53.2	53.4	53.3	0.42	0.59
Final BW, g	2,812^{b}	2,836^{b}	2,904^{a}	17	0.03
Days 1–21					
BWG, g	1,163	1,170	1,184	11	0.43
FI, g	2,356	2,405	2,401	19	0.18
F/G	2.03	2.06	2.03	0.02	0.58
Days 22–42					
BWG, g	1,596^{b}	1,613^{ab}	1,667^{a}	18	0.04
FI, g	4,575	4,580	4,598	24	0.17
F/G	2.87^{a}	2.84^{a}	2.76^{b}	0.02	0.03
Days 1–42					
BWG, g	2,759^{b}	2,783^{b}	2,851^{a}	22	0.02
FI, g	6,931	6,985	6,999	30	0.18
F/G	2.51	2.51	2.45	0.02	0.07

[a,b]Means in the same row with different superscripts differ ($P < 0.05$).
[1]Means represent 8 replicates with 40 birds per cage (n = 320 per treatment).
[2]BWG: body weight gain; FI: feed intake; F/G: feed-to-gain ratio.
[3]CON: basal diet; MSM: methylsulfonylmethane; MSM1: basal diet containing 0.15% methylsulfonylmethane; MSM2: basal diet containing 0.3% methylsulfonylmethane.
[4]Standard error of the means.

Meat Quality and Relative Organ Weight

The administration of MSM did not influence ($P > 0.05$) the relative weight of carcass yield (without the neck and feet), breast meat, abdominal fat, the liver, the gizzard, the pancreas, the thymus, the bursa of Fabricius, or the spleen (Table 4).

Dietary treatments did not influence ($P > 0.05$) pH_{45min}, lightness (L*), yellowness (b*), cook loss, and drip loss on days 1 and 3 (Table 5). Dietary supplementation with 0.3% MSM increased ($P < 0.05$) pH_{24h} in breast meat compared with CON. The inclusion of MSM increased ($P < 0.05$) WHC and redness (a*) and decreased ($P < 0.05$) TBARS and drip loss on day 5 of breast muscle in birds, compared with CON treatment.

Table 3. Effects of MSM on blood profiles in Pekin ducks.[1]

Item[2]	CON[3]	MSM1[3]	MSM2[3]	SEM[4]	*P*-value
SOD, U/mL	152^{b}	162^{ab}	175^{a}	3.38	0.03
GSH-PX, U/mL	278^{b}	289^{ab}	311^{a}	4.21	0.02
MDA, nmol/mL	5.03^{a}	4.37^{b}	3.89^{b}	0.15	0.03
T-AOC, U/mL	15.3^{b}	17.5^{ab}	21.7^{a}	1.67	0.02
IgG, μg/mL	102	110	108	3.03	0.38
IL-2, ng/mL	123^{b}	130^{ab}	137^{a}	3.25	0.03
IL-6, ng/mL	18.8^{b}	19.9^{ab}	21.7^{a}	0.53	0.04
IFN-γ, ng/mL	18.5^{a}	17.4^{a}	15.9^{b}	0.42	0.02
TNF-α, pg/mL	21.1^{a}	20.5^{a}	18.4^{b}	0.48	0.03

[a,b]Means in the same row with different superscripts differ ($P < 0.05$).
[1]Means represent 8 replicates with 8 birds per cage (n = 8 per treatment).
[2]SOD: superoxide dismutase; T-AOC: total antioxidative capacity; MDA: malondialdehyde; GSH-PX: glutathione peroxidase; IgG: immunoglobin G; IL-2: interleukin-2; IL-6: interleukin-6; TNF-α: tumor necrosis factor-α; IFN-γ: interferon gamma.
[3]CON: basal diet; MSM: methylsulfonylmethane; MSM1: basal diet containing 0.15% methylsulfonylmethane; MSM2: basal diet containing 0.3% methylsulfonylmethane.
[4]Standard error of the means.

Table 4. Effects of MSM on relative organ weight in Pekin ducks.[1]

Item	CON[2]	MSM1[2]	MSM2[2]	SEM[3]	*P*-value
Carcass yield, %	68.4	69.0	68.8	0.25	0.43
Breast meat, %	17.0	17.2	17.4	0.13	0.65
Abdominal fat, %	3.15	3.13	3.22	0.07	0.21
Liver, %	2.93	2.90	2.91	0.04	0.19
Gizzard, %	2.13	2.14	2.11	0.05	0.48
Pancreas, %	0.33	0.34	0.35	0.01	0.71
Thymus, %	3.60	3.57	3.52	0.05	0.42
Bursa of Fabricius, %	0.12	0.13	0.13	0.02	0.66
Spleen, %	0.13	0.14	0.13	0.02	0.32

[1]Means represent 8 replicates with 8 birds per cage (n = 8 per treatment).
[2]CON: basal diet; MSM: methylsulfonylmethane; MSM1: basal diet containing 0.15% methylsulfonylmethane; MSM2: basal diet containing 0.3% methylsulfonylmethane.
[3]Standard error of the means.

DISCUSSION

Growth Performance

This study showed that the inclusion of MSM (0.3%) improved final BW and BWG during the periods of days 22–42 and days 1–42 as well as reduced F/G during the period of days 22–42 in Pekin ducks. On the contrary, Hwang et al. (2017) reported no effect of MSM (0.03%) on BWG, FI, or F/G in Cherry Valley male ducks. Similarly, Liu and Zhou (2008) found that supplementation with MSM (0.025%) did not affect BWG or F/G in local Tianfu meat ducks. The difference in results compared with those of the present study may be due to the low dosage of MSM used in the previous experiments. To our knowledge, there are no other studies describing the effects of MSM on ducks. Therefore, we decided to compare our results with similar studies in poultry and pigs. In agreement with our results, Jiao et al. (2017) indicated that the supplementation of MSM (0.05–0.2%) increased BWG linearly during the period of days 1–29 and reduced F/G linearly during the period of days 1–14 and days 1–29 in broilers. However, Cho et al. (2005) showed that dietary MSM treatment (0.01%) did not affect ADG, average daily FI, and feed efficiency in growing-finishing pigs. The lack of MSM effect on nutrient digestibility may be one reason for the absence of positive effect on growth performance (Cho et al., 2005). Others researchers did not also observe any effect of MSM on egg production rates, egg weight, and F/G in laying hens (Park et al., 2010).

Table 5. Effects of MSM on meat quality in Pekin ducks.[1]

Item[2]	CON[3]	MSM1[3]	MSM2[3]	SEM[4]	*P*-value
pH_{45min}	5.91	5.92	5.95	0.04	0.37
pH_{24h}	5.54^{b}	5.59^{ab}	5.68^{a}	0.03	0.04
WHC, %	44.71^{b}	48.21^{a}	49.34^{a}	1.04	0.03
Cook loss, %	34.01	34.12	34.07	2.34	0.29
TBARS, mg MDA/kg	1.59^{a}	1.41^{b}	1.33^{b}	0.03	0.02
Meat color					
Lightness (L*)	45.87	45.79	45.85	1.43	0.38
Redness (a*)	13.21^{b}	17.03^{a}	18.29^{a}	0.48	0.02
Yellowness (b*)	4.40	4.37	4.41	0.09	0.42
Drip loss, %					
Day 1	1.76	1.73	1.71	0.07	0.61
Day 3	3.75	3.72	3.69	0.08	0.15
Day 5	6.27^{a}	6.11^{ab}	5.95^{b}	0.08	0.04

[a,b]Means in the same row with different superscripts differ ($P < 0.05$).
[1]Means represent 8 replicates with 8 birds per cage (n = 8 per treatment).
[2]WHC: water-holding capacity; TBARS: 2-thiobarbituric acid–reactive substances.
[3]CON: basal diet; MSM: methylsulfonylmethane; MSM1: basal diet containing 0.15% methylsulfonylmethane; MSM2: basal diet containing 0.3% methylsulfonylmethane.
[4]Standard error of the means.

Blood Profiles

It is reported that MSM exerted anti-inflammatory and antioxidant effects (Maranon et al., 2008; Kim et al., 2009). The enzymes of the antioxidant system (SOD, GSH-PX, and T-AOC) could play a key role in scavenging oxidative radicals, reducing oxidative damage, and maintaining the cell structure. In the present study, the supplementation of MSM (0.3%) increased SOD, GSH-PX, and T-AOC levels and decreased MDA levels in the serum, a finding that was consistent with that of a previous study because Cherry Valley male ducks fed with diets containing 0.03% MSM had higher serum SOD and catalase activities on days 21 and 42 (Hwang et al., 2017). The higher serum SOD activity indicated that MSM may provide more efficient free radical–scavenging activity in Pekin ducks. Other researchers also showed a significant reduction in MDA levels and increase in GSH-PX and catalase activities in rats (Amirshahrokhi et al., 2011). The IL-2 and IL-6 are involved in immune response, which can stimulate the proliferation of activated natural killer cells, B lymphocytes, T lymphocytes, and antibody production as well as the production of IgA, IgM, and IgG. As expected, serum IL-2 and IL-6 levels were increased by MSM supplementation (0.3%) in the present study. Besides, the MSM supplementation (0.3%) decreased the levels of proinflammatory cytokines TNF-α and IFN-γ, which indicated the anti-inflammatory effect that MSM had on ducks. Amirshahrokhi et al. (2011) indicated that MSM decreased TNF-α levels in rats, which may be due to the inhibition of nuclear factor kappa B (**NF-κB**) signaling (Kim et al., 2009). Similarly, MSM reduced inflammatory response to TNF-α in cardiac cells (Lindsey et al., 2018). Kim et al. (2014) explained that MSM suppressed hepatic tumor development through activation of apoptosis.

Meat Quality and Relative Organ Weight

In the present study, there were no differences in the relative weight of the carcass (without neck and feet), breast meat, abdominal fat, liver, gizzard, pancreas, thymus, bursa of Fabricius, or spleen. Similarly, Liu and Zhou (2008) indicated that the supplementation of MSM (0.025%) did not affect the percentage of the breast muscle or abdominal fat in local Tianfu meat ducks. Moreover, Jiao et al. (2017) observed no effect of MSM on the relative weight of breast meat, abdominal

fat, the liver, the gizzard, the bursa of Fabricius, or the spleen in broilers.

Water loss plays an important role in raw and processed meat products because it could affect sensory characteristics and nutritional value of meat (Hamm, 1985; Muhlisin et al. 2013). In the present study, it was found that the inclusion of MSM (0.3%) increased WHC. In agreement with our results, Hwang et al. (2017) reported that the supplementation of MSM (0.03%) increased WHC in Cherry Valley male ducks. The increased pH_{24h} could mirror the improved WHC in the present study. Gou et al. (2002) found that pH as a carcass characteristic of meat quality had a relationship with WHC of meat. However, Jiao et al. (2017) did not observe a positive effect of MSM (0.05–0.2%) on pH or WHC in broilers. Furthermore, in our study, it was found that the drip loss on the day 5 postmortem was decreased by MSM supplementation (0.3%). Similarly, MSM supplementation reduced drip loss linearly on the day 5 and day 7 postmortem in broilers (Jiao et al., 2017). Lee et al. (2009) indicated that the inclusion of MSM (0.03–0.05%) decreased drip loss on the day 2 postmortem in finishing pigs. Suryanti et al. (2014) demonstrated that duck meat containing a high concentration of unsaturated fats was susceptible to oxidation, which might lead to rancidity and deterioration in flavor and color. 2-Thiobarbituric acid–reactive substances reflected the concentration of secondary lipid oxidation products, which could result in off-flavors in meat (Juntachote et al. 2006). As expected, in the present study, the TBARS values were reduced after the supplementation of MSM, which was consistent with the findings of Hwang et al. (2017). They observed decreased TBARS levels in Cherry Valley male ducks fed with diets supplemented with 0.03% MSM from day 15 to 27 during cold storage. Lee et al. (2009) also found that the TBARS level during days 2–8 was decreased in finishing pigs fed with diets supplemented with 0.03–0.05% MSM. The reduced TBARS level may imply that MSM exerts potent antioxidant activities to scavenging free radicals. The supplementation of MSM increased redness (a*) in finishing pigs (Lee et al., 2009), broilers (Jiao et al., 2017), and ducks (Hwang et al., 2017). In agreement with these studies, in the present study, increased redness (a*) of breast meat was demonstrated in MSM treatments. The content of myoglobin pigments mainly affected meat color (Coggins, 2007). Yin and Faustman (1993) and Fernández-López et al. (2005) attributed the meat discoloration to the oxidation of myoglobin to metmyoglobin during storage. Therefore, the increased redness (a*) may be due to the antioxidative property of MSM, which delays the metmyoglobin formation. Furthermore, another reason may be due to the effect of MSM on heme-Fe binding in myoglobin. Lee et al. (2009) observed increased iron deposition in loin meat of finishing pigs fed with diets supplemented with 0.03–0.05% MSM. The iron content may influence the redness of meat (Mortimer et al., 2014). In the present study, we failed to observe positive effect of MSM on pH_{45min}, cook loss, lightness (L*), and yellowness (b*). Similarly, the lightness (L*) and yellowness (b*) were not affected by MSM in broilers (Jiao et al., 2017). Hwang et al. (2017) did not observe any effect of MSM on cook loss, lightness (L*), and yellowness (b*) in Cherry Valley male ducks.

CONCLUSIONS

The supplementation of MSM (0.3%) resulted in a positive effect on final BW, BWG and feed efficiency, immunity, antioxidant capacity, and meat quality in Pekin ducks. Based on the aforementioned results, it is suggested that MSM is a valuable natural feed additive product to improve duck meats.

ACKNOWLEDGMENTS

This study was supported by the National Key Research and Development Program of China (2016YFD0500505) and Sichuan Science and Technology Program (2018HH0083).

REFERENCES

Amirshahrokhi, K., S. Bohlooli, and M. M. Chinifroush. 2011. The effect of methylsulfonylmethane on the experimental colitis in the rat. Toxicol. Appl. Pharmacol. 253:197–202.

AOAC International 2002. Official Methods of Analysis of AOAC International, 17th ed. AOAC Int., Gaithersburg, MD.

Childs, S. J. 1994. Dimethyl sulfone (DMSO2) in the treatment of interstitial cystitis. Urol. Clin. North Am. 21:85–88.

Cho, J. H., B. J. Min, O. S. Kwon, K. S. Shon, Y. G. Jin, H. J. Kim, and I. H. Kim. 2005. Effects of MSM (Methyl Sulfonyl Methane) supplementation on growth performance and digestibility of CA and N in pigs. J. Kor. Soc. Food Sci. Nutr. 34:361–365.

Coggins, P. C. 2007. Attributes of muscle foods: color, texture, flavor. In: L. M. L. Nollet (Ed.), Handbook of Meat Poultry and Seafood Quality. Balckwell Publishing Professional, Ames, Iowa, p. 90.

Fernández-López, J., N. Zhi, L. Aleson-Carbonell, J. A. Perez-Alvarez, and V. Kuri. 2005. Antioxidant and antibacterial activities of natural extracts: application in beef meatballs. Meat Sci. 69:371–380.

Gou, P., J. Comaposada, and J. Arnau. 2002. Meat pH and meat fiber direction effects on moisture diffusivity in salted ham muscles dried at 5°C. Meat Sci. 61:25–31.

Gregory, P. J., M. Sperry, and A. F. Wilson. 2008. Dietary supplements for osteoarthritis. Am. Fam. Physician. 77:177–184.

Hamm, H. 1985. The effect of water on the quality of meat and meat products: problems and research needs. In: D. Simatos and J. L. Multon (Eds.), Properties of Water in Foods. M. Nijhoff, Dordrecht, Netherlands, pp. 591–602.

Honikel, K. O. 1998. Reference methods for the assessment of physical characteristic of meat. Meat Sci. 49:447–457.

Hwang, J. W., S. H. Cheong, Y. S. Kim, J. W. Lee, B. I. You, S. H. Moon, B. T. Jeon, and P. J. Park. 2017. Effects of dietary supplementation of oriental herbal medicine residue and methyl sulfonyl methane on the growth performance and meat quality of ducks. Anim. Prod. Sci. 57:948–957.

Jiao, Y., J. H. Park, Y. M. Kim, and I. H. Kim. 2017. Effects of dietary methyl sulfonyl methane (MSM) supplementation on growth performance, nutrient digestibility, meat quality, excreta microbiota, excreta gas emission, and blood profiles in broilers. Poult. Sci. 96:2168–2175.

Juntachote, T., E. Berghofer, S. Siebenhandl, and F. Bauer. 2006. The antioxidative properties of holy basil and galangal in cooked ground pork. Meat Sci. 72:446–456.

Kauffman, R. G., G. Eikelenboom, P. G. van der Wal, B. Engel, and M. Zaar. 1986. A comparison of methods to estimate water-holding capacity in post-rigor porcine muscle. Meat Sci. 18:307–322.

Kim, L. S., L. J. Axelrod, P. Howar, N. Buratovich, and R. F. Waters. 2006. Efficacy of methylsulfonylmethane (MSM) in osteoarthritis pain of the knee: a pilot clinical trial. Osteoarthritis Cartilage. 14:286–294.

Kim, Y. H., D. H. Kim, H. Lim, D. Y. Baek, H. K. Shin, and J. K. Kim. 2009. The anti-inflammatory effects of methylsulfonylmethane on lipopolysaccharide-induced inflammatory responses in murine macrophages. Biol. Pharm. Bull. 32:651–656.

Kim, J. H., H. J. Shin, H. L. Ha, Y. H. Park, T. H. Kwon, M. R. Jung, H. B. Moon, E. S. Cho, H. Y. Son, and D. Y. Yu. 2014. Methylsulfonylmethane suppresses hepatic tumor development through activation of apoptosis. World J. Hepatol. 6:98–106.

Lee, J. I., H. K. Min, J. W. Lee, J. D. Jeong, Y. J. Ha, S. C. Kwack, and J. S. Park. 2009. Changes in the quality of loin from pigs supplemented with dietary methyl sulfonyl methane during cold storage. Korean J. Food Sci. 29:229–237.

Lindsey, E. M. 2018. Methylsulfonylmethane decreases inflammatory response to tumor necrosis factor-α in cardiac cells. Am. J. Cardiovasc. Dis. 8:31–38.

Liu, H. F., and A. G. Zhou. 2008. Effects of plant extracts, cysteamine and methylsulfonylmethane on productive performance and slaughter characteristics in meat ducks. Nat. Prod. Res. Dev. 20:302–306.

Liu, J. B., P. C. Xue, S. C. Cao, J. Liu, L. Chen, and H. F. Zhang. 2018. Effects of dietary phosphorus concentration and body weight on postileal phosphorus digestion in pigs. Anim. Feed Sci. Tech. 242:86–94.

Liu, J. B., H. L. Yan, Y. Zhang, Y. D. Hu, and H. F. Zhang. 2019a. Effects of dietary energy and protein content and lipid source on growth performance and carcass traits in Pekin ducks. Poult. Sci. 98:4829–4837.

Liu, J. B., H. L. Yan, Y. Zhang, Y. D. Hu, and H. F. Zhang. 2019b. Effects of stale maize on growth performance, immunity, intestinal morphology and antioxidant capacity in broilers. Asian-Australas J. Anim. Sci. https://doi.org/10.5713/ajas.19.0224.

Maranon, G., B. Munoz-Escassi, W. Manley, C. Garcia, P. Cayado, M. S. de la Muela, B. Olabarri, R. Leon, and E. Vara. 2008. The effect of methyl sulphonyl methane supplementation on biomarkers of oxidative stress in sport horses following jumping exercise. Acta Vet. Scand. 50:45–50.

Mortimer, S. I., J. H. J. Van der Werf, R. H. Jacob, D. L. Hopkins, L. Pannier, K. L. Pearce, G. E. Gardner, R. D. Warner, G. H. Geesink, J. E. Hocking Edwards, E. N. Ponnampalam, A. J. Ball, A. R. Gilmour, and D. W. Pethick. 2014. Genetic parameters for meat quality traits of Australian lamb meat. Meat Sci. 96:1016–1024.

Muhlisin, D. S. Kim, Y. R. Song, H. R. Kim, H. J. Kwon, B. K. An, C. W. Kang, H. K. Kim , and S. K. Lee. 2013. Comparison of meat characteristics between Korean native duck and imported commercial duck raised under identical rearing and feeding condition. Korean J. Food Sci. Anim. Res. 33:89–95.

National Research Council 1994. Nutrient Requirements of Poultry. National Academy Press, Washington, DC, 9th revised.

Parcell, S. 2002. Sulfur in human nutrition and applications in medicine. Altern. Med. Rev. 7:22–44.

Park, S., S. Ahn, S. M. Hong, D. S. Kim, D. Y. Kwon, and H. J. Yang. 2010. The effects of the supplementation of opuntia humifusa water extracts and methyl sulfonyl methane on the laying productivity, egg quality and sensory characteristics. J. Kor. Soc. Food Sci. Nutr. 39:294–300.

Sullivan, Z. M., M. S. Honeyman, L. R. Gibson, and K. J. Prusa. 2007. Effects of triticale-based diets on finishing pig performance and pork quality in deep-bedded hoop barns. Meat Sci. 76:428–437.

Suryanti, U., V. P. Bintoro, U. Atmomarsono, Y. B. Pramono, and A. M. Legowo. 2014. Antioxidant activity of Indonesian endogenous duck meat marinated in ginger (*Zingiber officinale Roscoe*) extract. Int. J. Poult. Sci. 13:102–107.

U. S. Food and Drug Administration 2004. Guidance for Industry: Botanical Drug products. Accessed Sept. 2018. https://www.fda.gov/downloads/Drugs/GuidanceComplianceRegulatoryInformation/Guidances/ucm070491.pdf.

Witte, V. C., G. F. Krause, and M. E. Bailey. 1970. A new extraction method for determining 2-thiobarbuturic acid values of pork and beef during storage. J. Food Sci. 35:582–585.

Yan, H. L., S. C. Cao, Y. Li, H. F. Zhang, and J. B. Liu. 2019. Reduced meal frequency alleviates high-fat diet-induced lipid accumulation and inflammation in adipose tissue of pigs under the circumstance of fixed feed allowance. Eur. J. Nutr. https://doi.org/10.1007/s00394-019-01928-3.

Yin, M. C., and C. Faustman. 1993. The influence of temperature, pH, and phospholipid composition upon the stability of myoglobin and phospholipid: a liposome model. J. Agric. Food Chem. 41:853–857.

Zhang, C., K. K. Chen, X. H. Zhao, C. Wang, and Z. Y. Geng. 2019. Effect of L-theanine on the growth performance, immune function, and jejunum morphology and antioxidant status of ducks. Animal. 13:1145–1153.