

Sodium butyrate as an effective feed additive to improve performance, liver function, and meat quality in broilers under hot climatic conditions

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ABSTRACT This study was conducted to investigate the effects of dietary sodium butyrate (SB) supplementation on growth performance, liver function, antioxidant capacity, carcass characteristics, and meat quality in broilers under hot climatic conditions. A total of 288 one-day-old Arbor Acres broilers were randomly allocated to 4 dietary treatments as follow: CON, control diet without SB; T1, control diet with 300 mg/kg SB; T2, control diet with 600 mg/kg SB; and T3, control diet with 1,200 mg/kg SB. Each treatment had 6 replication pens and 12 broilers per pen. The results indicated that the BW on day 35; ADG from day 1 to 21, day 22 to 35, and day 1 to 35; and ADFI from day 22 to 35 linearly ($P < 0.05$) increased with SB supplementation. Interestingly, alanine aminotransferase and aspartate aminotransferase content in serum

were linearly ($P < 0.05$) decreased by SB supplementation. There was linear ($P < 0.05$) improvement in activity of superoxide dismutase and catalase in the liver, whereas the content of malondialdehyde was linearly ($P < 0.05$) decreased with the inclusion of SB. Increasing SB level linearly ($P < 0.05$) increased CP composition and decreased drip loss percentage on day 1 and 3 of breast muscle. Furthermore, there was linear ($P < 0.05$) improvement in activity of superoxide dismutase, glutathione peroxidase, and catalase, whereas the content of malondialdehyde showed decreasing trend ($P < 0.10$) with the inclusion of SB in breast muscle. In conclusion, SB can be used as an effective feed additive to improve growth performance, liver function, and meat quality of broilers under hot climatic conditions.

Key words: sodium butyrate, growth performance, anti-oxidant capacity, meat quality, broiler

2020 Poultry Science 99:5491–5500

<https://doi.org/10.1016/j.psj.2020.06.042>

INTRODUCTION

Despite the development in the design of animal farming house facilities and cooling technologies, animal health and production are still severely affected by high ambient temperature. Modern poultry genotypes seem to be particularly sensitive to heat stress because of higher metabolic activity (Settar et al., 1999; Deeb and Cahaner, 2002). It has been indicated that heat stress resulted in annual economic loss to the US poultry production industry of \$128 to \$165 million (St-Pierre et al., 2003). Heat stress has become a considerable challenge in the poultry industry because poultry production

and welfare are adversely affected by heat stress (Lara and Rostagno, 2013). Heat conditions caused changes in mortality (Quinteiro-Filho et al., 2010), growth performance (Sohail et al., 2012), metabolism (Mujahid et al., 2005), immune response (Niu et al., 2009; Bozkurt et al., 2012; Deng et al., 2012), and meat quality (Zhang et al., 2017) and disturb the balance between the production of reactive oxygen species and the antioxidant defense system (Feng et al., 2008; Liu et al., 2013). Proper nutritional strategy is a method to alleviate the detrimental effects on poultry health and production induced by heat stress. Abdel-Wareth et al. (2019) demonstrated that dietary symbiotic improved growth performance and meat quality of broilers in hot climatic regions. Hartanto et al. (2019) indicated that dietary nutmeg oil could inhibit lipid oxidation and maintain the liver function of broilers under heat stress.

A common nutritional strategy to improve poultry production while decreasing mortality is through antibiotics as a growth promoter. The use of antibiotics was questioned as a public concern owing to antimicrobial

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Received October 23, 2019.

Accepted June 13, 2020.

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resistance and residues. Butyrate is known as a safe alternative to antibiotics, received wide attention in the poultry industry. Butyrate is odorous and unstable; however, sodium butyrate (**SB**) was used as a replacement in the poultry production owing to its stable and nonodorous properties. It has been indicated that SB plays an important role as an energy source to gastrointestinal epithelial cells and has antimicrobial, anti-inflammatory, and antioxidant properties (Guilloteau et al., 2010; Zhang et al., 2011a,b; Liu et al., 2014; Song et al., 2017). Recent studies also indicated that SB could alleviate the detrimental effects of lipopolysaccharide or corticosterone-challenged broilers by improving growth performance, antioxidant capacity, and meat quality (Zhang et al., 2011a,b). Muscle meat quality is related to antioxidant capacity (Zhang et al., 2017). Former studies have reported that heat stress results in decreasing antioxidant enzyme activity in serum (Liu et al., 2013) and breast muscle (Lu et al., 2017) of broilers. Therefore, the negative effects of heat stress on meat quality may be associated with the change of antioxidant capacity. However, no practical animal study was conducted to evaluate the effect of dietary SB supplementation on meat quality and muscle antioxidant status of broilers under heat stress. Hence, we hypothesize that dietary SB may improve meat quality through decreasing oxidative stress under heat stress. Therefore, the purpose of this study was to evaluate the effect of dietary SB supplementation on muscle antioxidant status and meat quality of broilers under hot climatic conditions.

MATERIALS AND METHODS

Experiment Design and Dietary Treatments

A total of 288 1-day-old female Arbor Acres broilers were randomly allocated to 4 dietary treatments with 6 replication pens per treatment and 12 broilers per replication pen. The treatments were CON, control diet without SB; T1, control diet with 300 mg/kg SB; T2, control diet with 600 mg/kg SB; and T3, control diet with 1,200 mg/kg SB. The diet was provided in a mashed form and was formulated to meet or exceed the nutritional requirements of broilers during the starter (day 1–21) and grower (day 22–35) phases, as per the NRC (1994) recommendation (Table 1). The SB product was provided by a commercial company (Beijing Shengtaiyuan Biotechnology Co., Ltd., China) and contained 54% SB protected by a physical and chemical matrix of buffer salts.

Experimental Conditions

Broiler management procedures in this study were approved by the Animal Care and Use Committee of Guangdong Ocean University. Broilers of each replication were assigned in battery pens (124 cm length × 64 cm width × 40 cm height). Artificial light was provided 24 h per day by fluorescent lights and had free access to feed and tap water. The ambient temperature and relative humidity were recorded daily and are shown in Table 2. The average minimum and maximum temperature during

the experimental period were 28.80°C and 36.47°C (32.53°C ± 1.63°C) and relative humidity were 56.67 and 85.00% (73.77 ± 7.00%), respectively. The temperature and relative humidity were recorded at 08:00, 12:00, and 18:00 daily, and average temperature and relative humidity were calculated.

Performance Parameters

The BW was recorded on pen basis on day 1, 21, and 35. Feed consumption was recorded on pen basis every week to calculate ADFI and feed conversion ratio (**FCR**).

Serum Biochemical Parameters

On day 35, after 12 h fasting, 6 broilers per treatment (1 broiler from each replication pen) were randomly selected. The broilers were individually weighed, and then, blood samples were collected from the brachial vein into nonheparinized tubes and centrifuged at 3,000 × *g* for 10 min at 4°C to obtain serum. The serum samples stored at –20°C until analysis. The analysis of alanine aminotransferase (**ALT**) and aspartate aminotransferase (**AST**) was in accordance with the method described by Senanayake et al. (2015). The activities of superoxide dismutase (**SOD**), glutathione peroxidase (**GSH-Px**), and catalase (**CAT**) and the content of malondialdehyde (**MDA**) in serum were measured with corresponding assay kits (Nanjing Jiancheng Bioengineering Institute, Nanjing, China) as per the manufacturer's instructions.

Carcass Traits and Relative Organ Weight

After blood sample collection, the broilers were killed by cervical dislocation and exsanguination. The carcass weight was calculated by removing the feathers and blood, and the eviscerated weight was calculated by removing the head, feet, abdominal fat (fat surrounding the cloaca and gizzard), and all of the viscera except the lungs and kidneys. The dressing and eviscerated yield were expressed as the percentage of live BW. Breast and leg muscle and abdominal fat were excised and weighed to calculate the muscle and abdominal fat yield based on eviscerated weight, respectively. The left part of breast muscle was used to analyze meat quality, and the right part was immediately frozen and stored at –20°C for further analysis.

Breast Muscle Chemical Composition and Meat Quality

Breast samples were analyzed for DM, CP, crude fat, and ash in accordance with Association of Analytical Chemists methods (AOAC, 1995). Briefly, about 5 g of breast muscle (fresh weight) was weighted to determine the moisture and crude fat, about 0.2 g (DM basis) of sample was weighted to determine CP content, and about 2.5 g (DM basis) of sample was weighted to determine ash content.

Table 1. Ingredient composition and nutrient content of diets.

Item	Starter (day 1–21)	Grower (day 22–35)
Ingredients, %		
Corn	54.57	62.44
Soybean meal, 48% CP	29.95	25.58
Corn gluten meal, 60% CP	5.90	3.30
Soybean oil	5.50	4.89
Tricalcium phosphate	2.46	2.29
Limestone	0.89	0.75
Salt	0.20	0.20
DL-Met, 88%	0.07	0.07
L-Lys·HCl (78.4%)	0.06	0.08
Vitamin premix ¹	0.20	0.20
Mineral premix ²	0.20	0.20
Calculated composition		
ME, MJ/kg	12.95	12.74
CP, %	21.89	18.90
Ca, %	1.05	0.96
Lys, %	1.12	1.01
Met + Lys, %	0.90	0.86
Available P, %	0.81	0.73
Analyzed composition, %		
CP	21.12	20.02
Ca	1.03	0.95
Met + Lys	0.89	0.87
Available P	0.44	0.42

¹Provided per kilogram of complete diet: 12,8000 IU vitamin A, 1,600 IU vitamin D₃, 60 IU vitamin E, 1.6 mg vitamin K₃, 0.12 mg biotin, 50 mg choline, 1.2 mg folic acid, 32 mg Nicotinic acid, 16 mg pantothenic acid, 4.8 mg riboflavin, 2.4 mg thiamine (B₁), 3.2 mg vitamin B₆, and 0.03 mg vitamin B₁₂.

²Provided per kilogram of diet: Mg, 79 mg as manganese oxide; Zn, 60 mg as zinc oxide; Cu, 100 mg as copper sulfate; Fe, 120 mg as iron sulfate; I, 0.96 mg as potassium iodine; Co, 0.16 mg as cobalt sulfate and Se, 0.24 mg as sodium selenite.

The breast muscle pH was measured duplicate at a depth of 2.5 cm below the surface using a pH meter at 45 min (pH_{45 min}) and 24 h (pH_{24 h}) postmortem (Fisher Scientific, Pittsburgh, PA). Meat color was measured on 2 points of breast muscle at 45 min postmortem, the lightness, redness, and yellowness were measured using a Model CR-410 Chroma meter (Konica Minolta Sensing Inc., Osaka, Japan). Cooking loss was measured as described previously by Sullivan et al. (2007). For cooking loss determination, approximately 4 g sample was weighed, placed in a plastic bag, and cooked to an internal temperature of 75°C using a water bath; then, the cooked samples were allowed to cool for 30 min, blotted dry, and weighed. Cooking loss values were calculated based on the following equation, cooking loss (%) = (raw weight-cooked weight)/raw weight × 100. The drip loss from 0 to 1, 3, 5, 7 D was assessed from the muscle packaged in a transparent polythene bag and stored at 4°C for 1, 3, 5, and 7 D, after which the excess moisture was wiped out, and the breast samples were weighed (on day 1, 3, 5, 7); drip loss was measured using approximately 4 g of meat sample as per the plastic bag method described by Honikel (1998).

Antioxidant Enzyme Activity and Lipid Peroxidation in the Liver and Breast Muscle

For antioxidant enzyme activity and MDA content measurement, about 1 g frozen liver or breast muscle sample was homogenized in 9 mL of ice-cooled 0.86% sodium chloride solution and centrifuged at 3,000 × *g* for

10 min at 4°C. The supernatant was collected for further analysis. The protein concentration of the supernatant was determined by the Bradford method using BSA as the standard. The activity of SOD, GSH-Px, and CAT and the content of MDA were measured with corresponding assay kits (Nanjing Jiancheng Bioengineering Institute, Nanjing, China) as per the manufacturer's instruction.

Statistical Analysis

The pen was used as the experiment unit, and all data were analyzed with SAS 2003 (v. 9.1; SAS Institute Inc., Cary, NC) using the mixed procedure. All data were analyzed using 1-way ANOVA followed by Duncan's multiple range test to analyze differences among treatments. Orthogonal polynomial contrasts were used to study the linear and quadratic effects of dietary SB level. Differences were considered significant at $P < 0.05$, and $P < 0.10$ was considered as a trend.

RESULTS

Performance Parameters

The effects of SB on growth performance under hot climatic conditions are shown in Table 3. On day 1, no significant differences were observed on BW among the treatments; however, on day 21 and 35, there was a linear ($P < 0.05$) increase in BW associated with the inclusion of SB in the diet. From day 1 to 21, day 22

Table 2. The ambient temperature and relative humidity during experimental period.

Item	Temperature, °C				Humidity, %			
	08:00	12:00	18:00	Average	08:00	12:00	18:00	Average
Day 1	28.80	32.70	29.10	30.20	98.00	65.00	82.00	81.67
Day 2	30.80	30.90	31.00	30.90	83.00	85.00	78.00	82.00
Day 3	31.10	33.70	31.70	32.17	81.00	68.00	79.00	76.00
Day 4	31.20	34.50	31.20	32.30	79.00	64.00	81.00	74.67
Day 5	31.40	34.70	33.20	33.10	77.00	63.00	62.00	67.33
Day 6	30.00	35.20	33.80	33.00	82.00	58.00	56.00	65.33
Day 7	30.80	36.70	33.10	33.53	82.00	52.00	63.00	65.67
Day 8	31.60	36.80	35.10	34.50	77.00	58.00	56.00	63.67
Day 9	32.10	35.10	32.90	33.37	83.00	65.00	76.00	74.67
Day 10	30.30	31.70	31.70	31.23	85.00	66.00	72.00	74.33
Day 11	38.70	29.20	30.80	32.90	88.00	80.00	81.00	83.00
Day 12	28.20	32.10	31.70	30.67	84.00	77.00	72.00	77.67
Day 13	30.30	32.50	30.80	31.20	88.00	74.00	81.00	81.00
Day 14	29.20	34.40	29.20	30.93	91.00	67.00	80.00	79.33
Day 15	30.30	34.20	30.20	31.57	84.00	69.00	85.00	79.33
Day 16	31.30	33.10	31.10	31.83	80.00	67.00	81.00	76.00
Day 17	29.90	36.30	34.10	33.43	89.00	62.00	62.00	71.00
Day 18	32.10	36.60	34.10	34.27	81.00	61.00	66.00	69.33
Day 19	32.40	36.80	32.50	33.90	79.00	61.00	77.00	72.33
Day 20	32.70	38.50	32.20	34.47	70.00	56.00	74.00	66.67
Day 21	29.60	37.60	32.20	33.13	84.00	54.00	74.00	70.67
Day 22	29.80	34.40	30.50	31.57	83.00	68.00	84.00	78.33
Day 23	33.10	37.10	33.30	34.50	77.00	58.00	71.00	68.67
Day 24	30.10	37.20	36.20	34.50	84.00	56.00	59.00	66.33
Day 25	34.40	37.00	38.00	36.47	69.00	51.00	50.00	56.67
Day 26	30.50	38.00	36.20	34.90	79.00	52.00	59.00	63.33
Day 27	31.20	25.40	38.00	31.53	80.00	99.00	50.00	76.33
Day 28	29.60	34.90	33.80	32.77	77.00	66.00	67.00	70.00
Day 29	33.50	35.50	31.80	33.60	71.00	56.00	72.00	66.33
Day 30	28.20	29.40	28.80	28.80	87.00	86.00	82.00	85.00
Day 31	32.40	33.10	30.70	32.07	76.00	71.00	78.00	75.00
Day 32	38.70	29.20	30.80	32.90	88.00	80.00	81.00	83.00
Day 33	29.20	32.10	31.70	31.00	84.00	77.00	72.00	77.67
Day 34	30.30	32.50	30.80	31.20	88.00	74.00	81.00	81.00
Day 35	29.20	32.40	29.20	30.27	91.00	77.00	80.00	82.67

to 35, and day 1 to 35, there were linear ($P < 0.05$) improvements in ADG associated with the inclusion of SB. There was a linear increase in ADFI from day 22 to 35 with the inclusion of SB. No significant differences were observed in FCR among treatments.

Antioxidant Enzyme Activity and Lipid Peroxidation of Serum

No significant differences were observed in MDA content and the activity of CAT in serum among treatments (Figure 1). The activity of SOD and GSH-Px was higher ($P < 0.05$) in broilers fed the T3 diet than in the CON group.

Liver Function

Dietary SB supplementation significantly decreased ALT and AST levels compared with the CON group; there was a linear ($P < 0.05$) decrease in ALT and AST levels with the inclusion of SB (Figure 2). No differences were observed in the activity of GSH-Px in the liver among treatments (Figure 3). There was a linear ($P < 0.05$) improvement in activity of SOD and CAT in the liver with the inclusion of SB, whereas the content

of MDA shown a linear ($P < 0.05$) decrease with the inclusion of SB.

Carcass Traits, Breast Muscle Chemical Composition, and Meat Quality

No significant differences were observed in dressing, eviscerated, breast muscle, leg muscle, and abdominal fat yield (Table 4). There was a linear ($P < 0.05$) improvement in the breast muscle CP composition associated with the inclusion of SB, but no significant differences were observed in moisture, ether extract, or ash composition (Table 5). No significant differences were observed in pH_{45 min} or breast muscle color (lightness, redness, and yellowness) among treatments (Table 6). Cooking loss and drip loss on day 5 and 7 shown a linear decreasing trend ($P < 0.10$), and drip loss on day 1 and 3 shown a linear decrease associated with the inclusion of SB ($P < 0.05$).

Breast Muscle AntiOxidant Status

The antioxidant status of breast muscle is shown in Figure 4. There was a linear ($P < 0.05$) improvement in the activity of SOD, GSH-Px, and CAT with the inclusion of SB, whereas the content of MDA showed a decreasing trend ($P < 0.10$) with the inclusion of SB.

Table 3. Effects of sodium butyrate on growth performance of broilers.

Item	Sodium butyrate level ¹ , mg/kg				SE	P-value	
	CON	T1	T2	T3		Linear	Quadratic
BW (g)							
Day 1	32.83	31.67	31.83	31.67	0.85	0.3900	0.5621
Day 21	709.57 ^a	711.79 ^a	725.58 ^{a,b}	674.71 ^b	5.19	0.0009	<0.0001
Day 35	1449.67 ^c	1508.00 ^b	1549.67 ^a	1458.67 ^c	5.50	0.0112	<0.0001
ADG (g)							
Day 1–21	32.22 ^b	32.39 ^{a,b}	33.04 ^a	30.62 ^c	0.25	0.0013	<0.0001
Day 22–35	52.87 ^a	56.87 ^b	58.86 ^c	56.00 ^d	0.06	<0.0001	<0.0001
Day 1–35	40.48 ^c	42.18 ^b	43.37 ^a	40.77 ^c	0.16	0.0082	<0.0001
ADFI (g)							
Day 1–21	51.39 ^a	50.69 ^a	50.03 ^{a,b}	48.81 ^b	0.56	0.0031	0.6458
Day 22–35	106.44 ^b	111.84 ^{a,b}	112.37 ^{a,b}	115.29 ^a	2.04	0.0076	0.5495
Day 1–35	73.41	75.15	74.97	75.40	0.91	0.1690	0.4808
FCR							
Day 1–21	1.60	1.57	1.51	1.59	0.02	0.4840	0.0063
Day 22–35	2.01	1.97	1.91	2.06	0.04	0.6503	0.0173
Day 1–35	1.81	1.78	1.73	1.85	0.07	0.5825	0.0030

^{a,b,c}Within the same row with different superscripts differ ($P < 0.05$).

Abbreviation: FCR, feed conversion ratio.

¹Sodium butyrate level: CON, control diet without sodium butyrate; T1, sodium butyrate at 300 mg/kg; T2, sodium butyrate at 600 mg/kg; T3, sodium butyrate at 1,200 mg/kg.

DISCUSSION

Poultry species are more susceptible to heat stress owing to limited heat dissipation capacity associated with lacking sweat glands and covering firm feathers and high body temperature (Yahav et al., 2004). As previously reported, exposing broilers to high temperature leads to behavioral, physiological and immunologic responses, which impose detrimental effects on growth performance and feed conversion efficiency (Sahin et al., 2010). The results of

present study showed that dietary SB had beneficial effects on BW, ADG, and ADFI when supplemented at levels of 300 mg/kg or 600 mg/kg; these results were in agreement with those of previous studies, which indicated that dietary butyric acid or its sodium salt had positive effects on performance by increasing feed intake, weight gain, and feed conversion efficiency (Wu et al., 2016; Sikandar et al., 2017). However, negative effects were observed on BW on day 21, as well as ADG and ADFI from day 1 to 21 with a supplemented level at 1,200 mg/kg. This is in

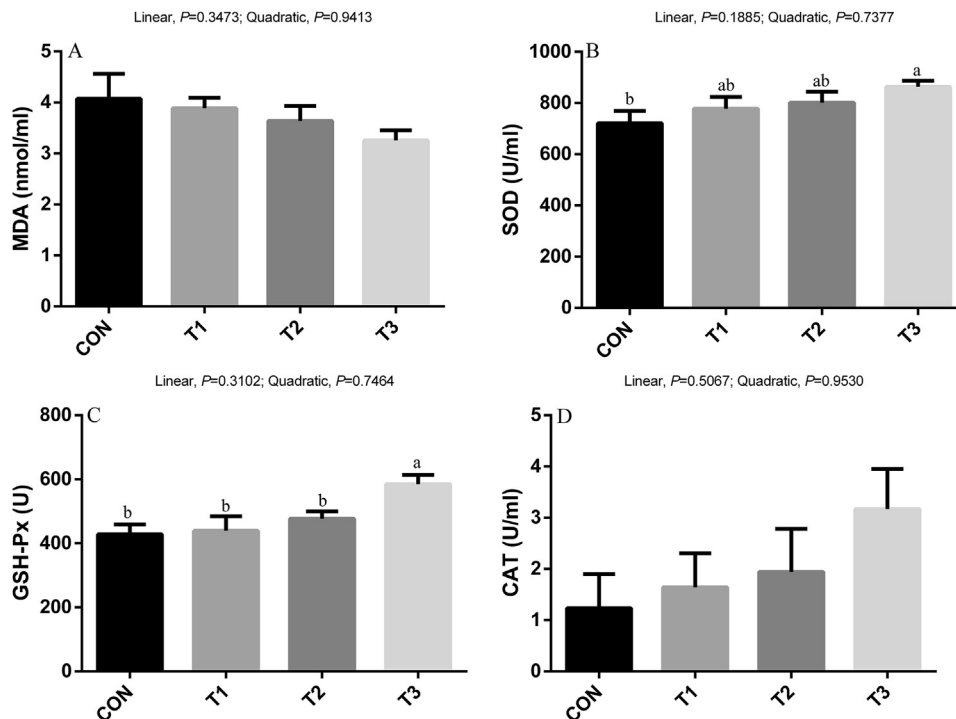


Figure 1. Effects of sodium butyrate on antioxidant indices and lipid peroxidation in serum of broilers. Values are mean \pm SE. The values having different superscript letters are different ($P < 0.05$). ^{a,b}Means with different superscripts differ ($P < 0.05$). Abbreviations: CAT, catalase; CON, control diet without sodium butyrate; GSH-Px, glutathione peroxidase; MDA, malondialdehyde; SOD, superoxide dismutase; T1, sodium butyrate at 300 mg/kg; T2, sodium butyrate at 600 mg/kg; T3, sodium butyrate at 1,200 mg/kg.

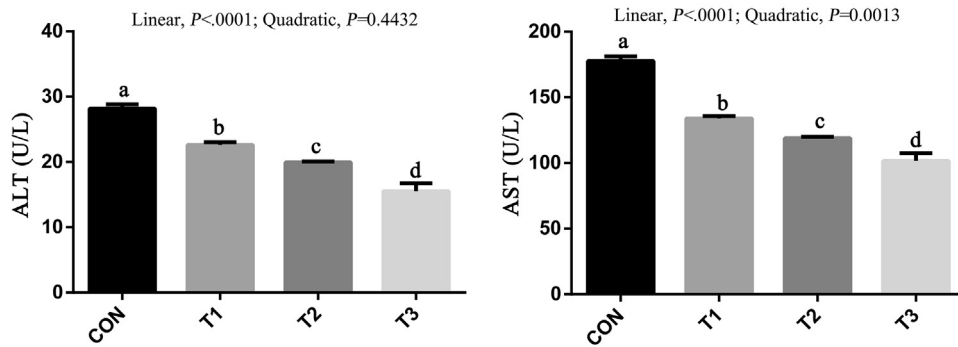


Figure 2. Effects of sodium butyrate on alanine aminotransferase (ALT) and aspartate aminotransferase (AST) in serum of broilers. Values are mean \pm SE. The values having different superscript letters are different ($P < 0.05$). ^{a,b,c,d}Means with different superscripts differ ($P < 0.05$). Abbreviations: CON, control diet without sodium butyrate; T1, sodium butyrate at 300 mg/kg; T2, sodium butyrate at 600 mg/kg; T3, sodium butyrate at 1,200 mg/kg.

agreement with the study by [Hu and Guo \(2007\)](#), who indicated that FCR was significantly increased with SB at the level of 2,000 mg/kg; it has been suggested that overuse of SB had negative effects on performance. Broilers subjected to chronic heat stress had impaired growth performance, reduced feed intake, lower BW, and lower feed conversion efficiency ([Niu et al., 2009](#); [Sohail et al., 2012](#)). Besides, dietary SB significantly alleviated the BW loss induced by stress treatment ([Zhang et al., 2011a,b](#); [Jiang et al., 2015](#)). However, no beneficial effects on performance were also reported by other studies ([Mahdzvi and Torki, 2009](#); [Aghazadeh and TahaYazdi, 2012](#); [Zou et al., 2019](#)). These inconsistent results indicate that SB may play a more effective role on broilers with stress challenge.

Exposure to heat stress may disturb the balance between oxidative stress and antioxidant defense system via increasing lipid peroxidation and depleting antioxidant enzymes ([Azad et al., 2010](#); [Yang et al., 2010](#); [Liu et al., 2013](#)), eventually contributing to the increase in nutrient expenditure and oxidative damage ([Hall et al., 2010](#); [Sahin et al., 2010](#)). In the present study, SB supplementation increased the activity of SOD and GSH-Px in serum, reduced the content of MDA, and increased the activity of SOD and CAT in the liver, as well as reduced the content of MDA and increased the activity of SOD, GSH-Px, and CAT in breast muscle. It has reported that under thermoneutral temperature, SB supplementation reduced the content of MDA and increased the activity of SOD, CAT, and total antioxidant capacity ([Zhang](#)

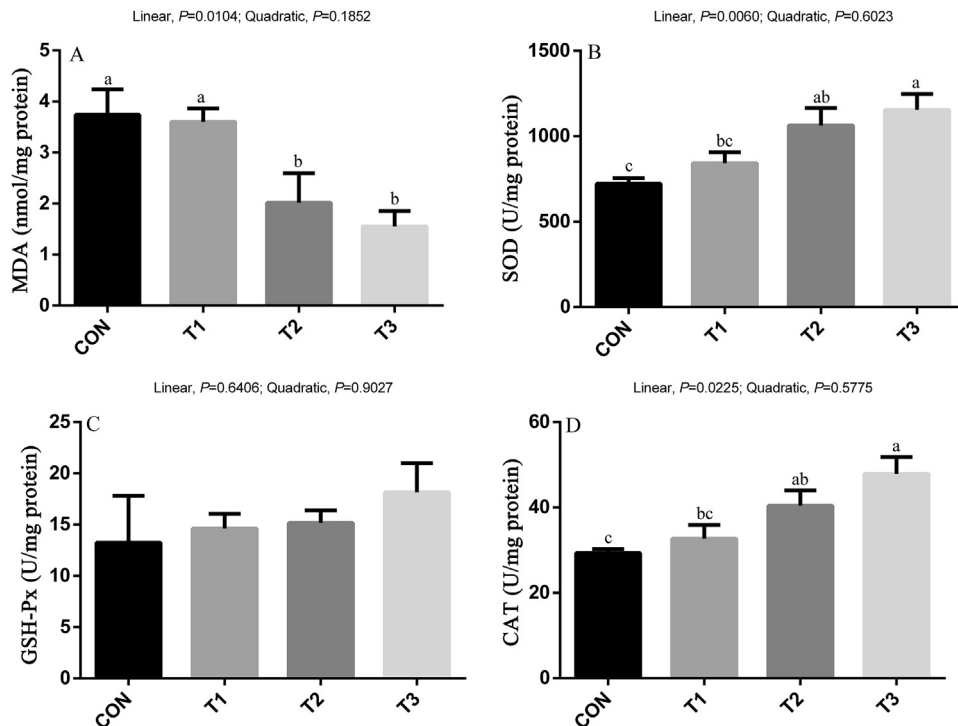


Figure 3. Effects of sodium butyrate on antioxidant indices and lipid peroxidation in the liver of broilers. Values are mean \pm SE. The values having different superscript letters are different ($P < 0.05$). ^{a,b,c}Means with different superscripts differ ($P < 0.05$). Abbreviations: CAT, catalase; CON, control diet without sodium butyrate; GSH-Px, glutathione peroxidase; MDA, malondialdehyde; SOD, superoxide dismutase; T1, sodium butyrate at 300 mg/kg; T2, sodium butyrate at 600 mg/kg; T3, sodium butyrate at 1,200 mg/kg.

Table 4. Effects of sodium butyrate on carcass traits of broilers.

Item	Sodium butyrate level ¹ , mg/kg				SE	P-value	
	CON	T1	T2	T3		Linear	Quadratic
Carcass traits ² , %							
Dressing	91.10	90.37	90.25	91.47	0.71	0.7668	0.1884
Eviscerated	75.78	74.68	73.82	74.33	0.75	0.1359	0.2953
Breast muscle	20.94	20.04	20.44	21.91	1.22	0.5508	0.3432
Leg muscle	23.23	23.17	23.04	23.89	0.85	0.6331	0.5988
Abdominal fat	2.27	2.56	1.89	2.31	0.30	0.6872	0.8347

¹Sodium butyrate level: CON, control diet without sodium butyrate; T1, sodium butyrate at 300 mg/kg; T2, sodium butyrate at 600 mg/kg; T3, sodium butyrate at 1,200 mg/kg.

²Dressing, abdominal fat, and eviscerated yield percentages were calculated by dividing these traits by final live weight after fasting. The percentages of breast muscle and thigh muscle were calculated as a percentage of eviscerated carcass weight.

et al., 2011b; Wu et al., 2018). In addition, several studies indicated that SB can alleviate negative effects associated with corticosterone-induced oxidative stress (Zhang et al., 2011a; Jiang et al., 2015). Based on the results of the present study, the improved antioxidant capacity of broilers observed in the SB-supplemented groups suggested that SB-induced effects were independent of the presence of heat stress, although the study on the antioxidant capacity of butyric acid or SB is relative few, especially, in broilers. Hamer et al. (2009) indicated that rectal administration of butyrate enhanced the colonic antioxidant capacity of healthy patients by increasing glutathione content. Sauer et al. (2007) demonstrated that butyrate attenuated H₂O₂-induced DNA damage and increased CAT activity in human colon cells in vitro. However, the mechanism by how butyrate or its sodium salt attenuates oxidative stress remains unknown. Therefore, the antioxidant property of butyric acid or its sodium salt needs to be further studied.

The liver that plays a major role in controlling glucose storage and flux is known to be the hub of the metabolism. Heat stress is known to induce tissue injury and severe liver damage in ducks (Zeng et al., 2014), and increased serum level of AST demonstrated hepatocyte and liver dysfunction (Tessari et al., 2010). The present study indicated that dietary SB decreased the AST and ALT level; it can be postulated that SB supplementation improved liver function under hot climatic conditions.

It has been reported that heat stress had negative effects on meat chemical composition and quality, decreased the proportion of breast muscle, increased

the proportion of thigh muscle and fat deposition, and decreased the protein content (Imik et al., 2012a; Dai et al., 2012; Zhang et al., 2012). However, no significant differences were observed in relative weight of breast muscle, leg muscle, or abdominal fat in the present study but CP composition in breast muscle has been increased with SB supplementation under hot climatic conditions. In addition, dietary SB supplementation improved meat quality by posing a positive effect on pH_{24 h}, cooking loss, and drip loss. Generally, the pH variation in muscle is due to glycogenolysis, heat stress increased glycogen breakdown, and the pH decreased postslaughter, which directly reflect muscle acid content and influence shelf life, water-holding capacity, and protein denaturation (Briskey and Wismer, 1961; Sams, 1999; Ahmed et al., 2016). The drip loss and cooking loss are the important indicators of water-holding capacity and reflect the juiciness of meat (Rasmussen and Andersson, 1996). In the present study, there was a significant decrease in drip loss of breast muscle on day 1 and 3, which is in agreement with the results reported by Zhang et al. (2011a), who indicated that dietary SB decreased 24-h drip loss of corticosterone-challenged broilers. However, no significant differences were observed in cooking loss. Lipid peroxidation is one of the most important factors causing deterioration of meat quality, which leads to flavor and texture problems, alter appearance, and decrease nutritive value (Salih et al., 1987; Fernández et al., 1997). Malondialdehyde is the main end product of lipid peroxidation, and its concentration reflects the lipid peroxidation in muscle (Janero, 1990). In the

Table 5. Effects of sodium butyrate on the chemical composition of breast muscle.

Item, %	Sodium butyrate level ¹ , mg/kg				SE	P-value	
	CON	T1	T2	T3		Linear	Quadratic
Moisture	71.47	71.63	72.18	73.25	1.14	0.2615	0.6947
CP	25.59 ^a	26.86 ^{a,b}	26.23 ^{a,b}	27.16 ^b	0.43	0.0446	0.6938
Ether extract	4.84	4.64	4.70	4.68	0.51	0.8591	0.8656
Ash	5.32	5.09	5.27	5.15	0.24	0.7473	0.8224

^{a,b}Within the same row with different superscripts differ ($P < 0.05$).

¹Sodium butyrate level: CON, control diet without sodium butyrate; T1, sodium butyrate at 300 mg/kg; T2, sodium butyrate at 600 mg/kg; T3, sodium butyrate at 1,200 mg/kg.

Table 6. Effects of sodium butyrate on meat quality of broilers.

Item	Sodium butyrate level ¹ , mg/kg				SE	P-value	
	CON	T1	T2	T3		Linear	Quadratic
pH _{45min}	6.73	6.79	6.88	6.71	0.05	0.9015	0.0414
pH _{24h}	6.56 ^b	6.70 ^a	6.68 ^a	6.60 ^{a,b}	0.04	0.4836	0.0089
Color indexes, 45 min postmortem							
Lightness (L*)	52.42	49.45	51.24	50.30	0.97	0.3047	0.3065
Redness (a*)	10.26	10.35	10.29	10.53	0.14	0.2230	0.6022
Yellowness (b*)	8.81	8.82	8.94	8.92	0.15	0.5062	0.9366
Cooking loss, %	25.77	24.74	19.75	19.55	0.03	0.0897	0.8912
Drip loss, %							
Day 1	3.70 ^a	2.56 ^{a,b}	2.44 ^{a,b}	1.37 ^b	0.01	0.0077	0.9451
Day 3	6.09 ^a	4.42 ^{a,b}	4.58 ^{a,b}	3.48 ^b	0.01	0.0165	0.6704
Day 5	7.74	6.04	6.26	5.47	0.01	0.0677	0.5581
Day 7	9.01	7.71	7.79	6.92	0.01	0.0905	0.7841

^{a,b}Within the same row with different superscripts differ ($P < 0.05$).

¹Sodium butyrate level: CON, control diet without sodium butyrate; T1, sodium butyrate at 300 mg/kg; T2, sodium butyrate at 600 mg/kg; T3, sodium butyrate at 1,200 mg/kg.

present study, dietary SB supplementation decreased MDA content in breast muscle, indicating that SB supplementation decreased lipid peroxidation of breast muscle, which may have beneficial effects on meat quality and shelf life. As expected, dietary SB supplementation significantly improved antioxidant status in the breast muscle by increasing the activity of SOD, GSH-Px, and CAT, which was similar to the results reported by Zhang et al. (2011a), who reported that dietary SB alleviated the negative effects of corticosterone-challenged broilers through enhancing CAT activity and decreasing the MDA level. Meat quality has a close relationship with muscle antioxidant status. Numerous studies in

broilers indicated that dietary supplementation with antioxidant nutrients, such as vitamin E (Olivo et al., 2001; Hashizawa et al., 2013), ascorbic acid, α -lipoic acid (Imik et al., 2012b), and resveratrol (Zhang et al., 2017), can improve muscle antioxidant status, and finally improve meat quality. The studies on the antioxidant capacity of butyric acid or its sodium salt are limited, especially in breast muscle. Until now, the effects of SB on meat quality are only studied in corticosterone-induced oxidative stress broilers, the mechanism of SB changing breast muscle antioxidant status remains unknown, and the antioxidant property of SB is interesting, which needs to be further studied.

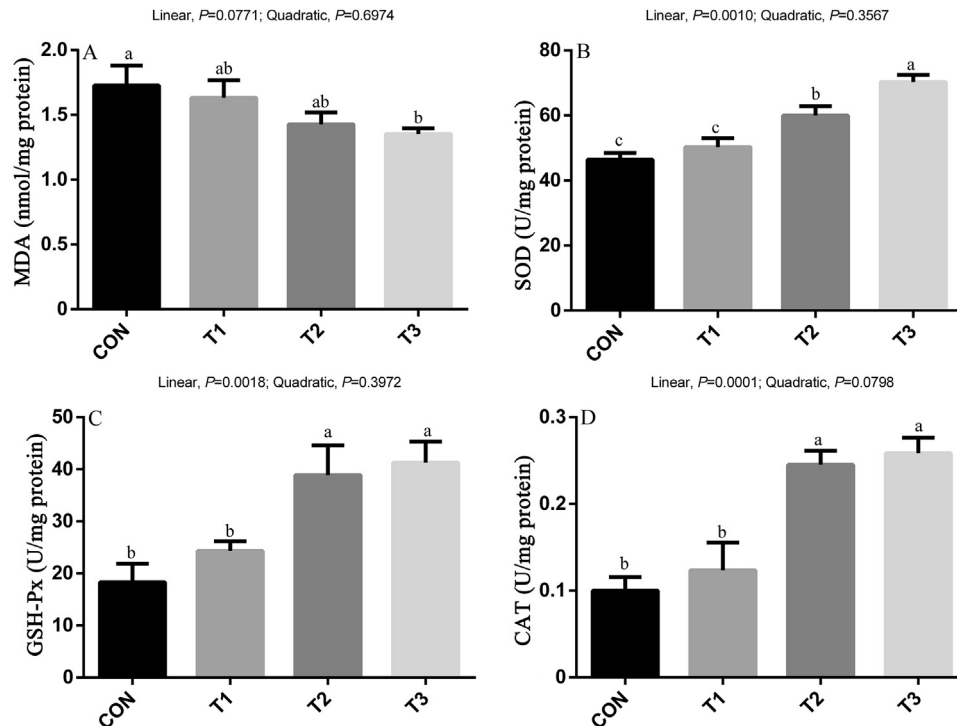


Figure 4. Effects of sodium butyrate on antioxidant indices and lipid peroxidation in breast muscle of broilers. Values are mean \pm SE. The values having different superscript letters are different ($P < 0.05$). ^{a,b,c}Means with different superscripts differ ($P < 0.05$). Abbreviations: CAT, catalase; CON, control diet without sodium butyrate; GSH-Px, glutathione peroxidase; MDA, malondialdehyde; SOD, superoxide dismutase; T1, sodium butyrate at 300 mg/kg; T2, sodium butyrate at 600 mg/kg; T3, sodium butyrate at 1,200 mg/kg.

CONCLUSIONS

In conclusion, the results of the present study indicate that SB can be used as an effective feed additive to improve growth performance, liver function, and meat quality of broilers under hot climatic conditions. Furthermore, SB addition, particularly at a dose of 1,200 mg/kg alleviated the oxidative stress induced by high ambient temperature in breast muscle and the liver, as a consequence, might improve the meat quality and liver function of broilers.

ACKNOWLEDGMENTS

Financial support provided by program for scientific research start-up funds of Guangdong Ocean University (101402/R18005) and Key Platform Project of Innovation strong school Engineering by Department of Education of Guangdong Province (2018302), is gratefully acknowledged.

Conflict of Interest Statement: No potential conflict of interest was reported by the authors.

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