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Effects of increasing dietary sodium selenite and selenium yeast levels on growth performance, meat quality and muscle anti-oxidative capacity of broilers

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Abstract

The objective of this experiment was to assess the effects of dietary sodium selenite and selenium (Se) yeast levels on growth performance, meat quality and muscle anti-oxidative capacity of broilers. A total of 360 1-day-old Cobb broilers were randomly assigned to 5 dietary treatments for 6 weeks. Diets (corn-soybean meal based diets) were supplemented with 0 mg/kg, 0.3 mg/kg and 0.6 mg/kg sodium selenium, and 0.3 mg/kg and 0.6 mg/kg selenium yeast, respectively. The results showed that Feed/Gain was significantly decreased with the increase of Se supplemental level during day 1-21 ($P < 0.05$), and body weight gain and Feed/Gain of broilers were improved with the increase of Se supplemental level by day 22 to 42 ($P < 0.05$). The dietary Se levels significantly affected the a*, cohesion, adhesion, chewing and recovery values of meat as well ($P < 0.05$). Se supplementation in diets also increased DPPH, hydroxyl radical scavenging and SOD, but significantly decreased TBARS and POV values compared to control ($P < 0.05$). The biological utilization rates of organic Se against inorganic Se were 116.0%, 123.1%, 109.7%, 109.8%, and 135.2%, respectively. The present results supported that organic Se was more bio-available and more effective in terms of growth performance, meat quality, muscle antioxidant and organ deposition efficiency compared to inorganic selenium. Therefore, the addition of 0.6 mg/kg selenium yeast (SY) during broiler breeding was the most effective.

Keywords: broilers; growth performance; anti-oxidative capacity; meat quality; selenium.

Practical Application: Selenium is widely used as a feed additive in livestock and poultry production, but there are no reports on the growth performance, meat quality, organ selenium enrichment and antioxidant capacity of broiler chickens with different selenium sources and selenium levels. In this study, the effects of the two selenium sources on the growth performance, meat quality and muscle antioxidant indexes of broiler chickens were compared by adding organic selenium and inorganic selenium to the diet, which provided theoretical support for the application of selenium in poultry production.

1 Introduction

The color, texture, and flavor of meat influence consumer choice, while the richness of trace elements in meat stimulates consumer demand (Sottero et al., 2019). Selenium (Se), as a trace element, is essential for organisms to perform their vital functions. Se is one of the essential nutrients in the human body, which can regulate the synthesis of glutathione peroxidase in the body, and protect cells apart from damage and maintain the function of cell membranes. At the same time, Se is also irreplaceable in the body's immune function, and has the effects of enhancing human immunity, anti-aging, and anti-tumor (Nguyen et al., 2022; Zhang et al., 2022). Related studies have found that Se supplementation is important for animal and human health as well as for ecological improvement (Liu et al., 2022). Adequate amounts of Se in the organism have an important role in maintaining normal muscle function (Pappas et al., 2012; Chen et al., 2017; Zoidis et al., 2018). Se deficiency leads to a decrease in the expression and activity of related selenoproteins, causing the development of muscle degenerative diseases such as Keshan's disease in humans, mulberry heart disease in pigs, and white muscle diseases in foals (Delesalle et al., 2017; Hosnedlova et al., 2017).

The bio-availability of Se in animals and its pharmacological and toxicological effects are related to its chemical form (Han et al., 2017). Adding a certain amount of organic Se to the diet has a certain degree of improvement on the growth performance, serum antioxidant index and meat quality of animals. It has also been reported that organic Se exhibits higher efficiency than inorganic Se in reducing the frequency of pectoralis PSE meat (Bakhshalinejad et al., 2019; Mariezcurrena-Berasain et al., 2022). In poultry farming, there are two main sources of Se supplementation, namely inorganic Se (mainly sodium selenite, Na_2SeO_3) and organic Se (mainly Se-Yeast or Se-Met preparations). Sodium selenite plays an important role in improving growth and health of poultry as a conventional Se sources in poultry diets (Han et al., 2017). Related studies had shown that organic Se is more readily absorbed and utilized by the organism compared to inorganic Se (Attia et al., 2010; Delezie et al., 2014) .

Although some previous studies have investigated the toxic levels of dietary Se in poultry production (Michalczuk et al., 2021), there was a lack of data regarding comparison of the growth performance, meat quality, and organ Se enrichment and antioxidant capacity of broilers.

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Therefore, the effects of the two kinds of Se sources on the growth performance, meat quality and muscle antioxidant indexes of broilers were compared by adding organic Se and inorganic Se to the diet in this study, and which provided reference materials for the application of organic Se in poultry production and new ideas for the development of Se-rich muscle products.

2 Materials and methods

2.1 Ethics statement

The protocol was reviewed and approved by the Animal Care and Use Committee of Gansu Agricultural University. All procedures were carried out in strict accordance with the recommendations in the Guide for Guidelines for Experimental Animals of the Ministry of Science and Technology (Beijing, China), and all efforts were made to minimize suffering (AEC-CAAS-20191003).

2.2 Broilers management and experimental design

A total of 360 Cobb broilers (one-day-old) were randomly allocated into five dietary treatments with six replicates and twelve broilers in each. The feeding period was 42 d, and which was divided into two stages: starter (0-21 d) and finisher (22-42 d). The basic experimental diets were formulated according to the nutritional requirements of China's agricultural industry standard for raising chickens (NY/T33-2004). The Se content of basal diets was 0.138 mg/kg on a dry matter basis. The ingredient composition and estimated nutrient content of the experimental basal diets are given in Table 1. This diet was supplemented with sodium selenite or Se yeast at 0.3 and 0.6 mg/kg feed, respectively.

Table 1. Ingredient composition and Nutrient Content of the Basal Diets.

Ingredients	Starter (1 to 21 d; g/kg)	Finisher (22 to 42 d; g/kg)
Corn	450.17	500.45
Vegetable oil	40.10	50.00
Soybean meal	220.43	160.50
Corn gluten meal	30.30	30.00
Cottonseed meal	80.00	80.00
Rice bran	70.00	70.00
DDGS	50.00	50.00
Calcium phosphate dibasic	10.70	10.70
Limestone	10.20	10.20
Salt (NaCl)	3.50	3.50
DL-methionine	1.50	1.50
L-lysine	4.00	4.50
Premix	10.00	10.00
Chloride choline	2.00	2.00
Sum	1000.00	1000.00
Calculated Nutrient Content		
ME, MJ/kg	12.03	12.10
CP, g/kg %	210.50	190.50
Ca, g/kg %	9.50	7.50
Available P, g/kg	4.50	3.50
Digestible Lys, g/kg	10.20	10.05
Digestible Met, g/kg	4.40	4.30
Se, mg/kg	0.40	0.50

Premix provided the following diet per kilogram: vitamin A, 11,000 IU; Vitamin D3, 3025 IU; Vitamin E, 22 mg; Vitamin K3, 2.2 mg; Vitamin B1, 1.65 mg; Vitamin B2, 6.6 mg; Vitamin B6, 3.3 mg; Vitamin B12, 17.6 g; Niacin, 22 mg; Pantothenic acid, 13.2 mg; Folic acid, 0.33 mg; Biotin, 88 g; Choline chloride, 500 mg; Iron, 48 mg; Zinc, 96.6 mg; Manganese, 101.76 mg; Copper, 10 mg; Iodine, 0.96 mg; Cobalt, 0.3 mg; The ME, CP, Ca, Available P, Lys, Met of basal diets were calculated value, but the Se content was measured value.

2.3 Growth performance and health status

All broilers were raised in three-tier battery cages with 12 broilers in one individual experimental unit (cages) (160 × 70 cm) with 20 h of light/day through-out the trial. The experiment was conducted with the temperature maintained at 34 °C at the arrival of the bird in an environmentally controlled room and gradually decreased. A total of 30 replicates of the 5 treatments were randomly distributed into 30 cages in the chicken house. Each cage is equipped with a feeding trough and 4 nipple drinkers. Chicks were provided with water and feed *ad libitum*. This experiment was conducted under strict bio-security measures. The broilers were vaccinated against Newcastle Disease (7 and 21 d post-hatch) and Infectious Bursal Disease (14 and 28 d post-hatch). At 0, 21 and 42 days of feeding for determination of growth performance, including body weight gain (BWG), feed intake (FI), and feed gain ratio (F/G). Mortalities and post-mortem weight were recorded daily for the calculation of mortality, body weight gain, and mortality-corrected F/G.

2.4 Meat quality

At the end of the experiment, one bird per replicate with body weight near the replicate average value (i.e., 6 broilers per treatment) was selected and weighed from each cage. The selected birds were euthanized by CO_2 inhalation and then immediately dissected to collect a thigh muscle sample. The pH was measured by portable pH-meter (Testo 205 pH meter, Lenzkirch, Germany) and average values at three different points were obtained for each sample. CIE (International Commission on Lumination) lightness (L*), redness (a*), and yellowness (b*) value measurements were analyzed using a colorimeter (Konica Minolta CR-300, Minolta Co., Ltd., Osaka, Japan) at 24 h after slaughter and were calculated for different points as the average of 5 repetitions; while flakes of fat and connective tissue were avoided. Quality and structural indices, such as hardness, elasticity, adhesion, mastication and recovery, were determined using the model in Texture meter (Universal TA, Henan, China). Cooking loss values of samples were determined according to outlined by Renaudeau & Mourot (2007). Before cooking, meat samples were dried to keep the surface moisture away and weighed accurately. Then the muscle samples were put in cooking bags and cooked in a water bath until a core temperature of reached to 70 °C was reached. Finally, the packaging was subsequently removed and the samples were dried and weighted again as the same process. The cooking loss rate of meat sample was calculated according to the following Formula 1:

$$\text{Cooking loss}(\%) = \frac{M1 - M2}{M1} \times 100\% \quad (1)$$

In the formula, M1 is the mass of meat samples before cooking (g), M2 is the mass of meat samples after cooking (g).

Same after cooking, each muscle strips were sampled along parallel with the muscle fibers orientation using an equipped sampler with a 30 kg tension/compression load cell, and the shear force values were determined with a Warner-Bratzler shear force (WBSF) (model TA-XT2i, Stable Micro Systems, UK). The average value of five replicates was used for statistical analysis.

2.5 Chemical analysis

One gram of frozen muscle samples was homogenized in 9 mL of ice-cold 0.9% saline solution, and the homogenate was centrifuged at 4000 rmp for 15 min at 4°C. The supernatant was then used for further analysis. Superoxide dismutase (SOD) activity was determined using an assay kit purchased from Nanjing Jiancheng Institute of Biological Engineering (Nanjing, China). The POV (Peroxide Value) was expressed as the unit of mmol O_2/kg muscle. TBARS (Thiobarbituric acid-reactive substances) was calculated from a standard curve of MDA (Malonaldehyde) and was expressed as the unit of mg MDA/kg muscle (Borella et al., 2019).

To determine Se, feeds and meat samples were digested using the MDS-2000 microwave oven in a mixture of nitric acid (HNO_3) and hydrogen peroxide (H_2O_2) (LabX, Midland, ON, Canada). The Se content assay of meat and organ was performed following the method of Pan et al. (2007) using an AF-610A atomic fluorescence spectrometer (Beijing Beifen-Ruili Analytical Instrument Co., Ltd., Yangzhou, China). To determine the concentration of lactate (LA), muscle samples frozen in liquid nitrogen were homogenized in 4.5 mL of normal saline, and centrifuged at 2000 × g at 4 °C, and then 1 mL of the supernatant was diluted with 4 mL of distilled water, mix with 1 mL of enzyme reaction mixture and 0.2 mL of developer and add 2 mL of terminator. Lactate content was used to determine the concentration of spectrophotometrically (530 nm) using a commercial kit (Nanjing Jiancheng Bioengineering Institute, Nanjing, China).

2.6 Free radical scavenging activity of thigh muscles

2,2-Diphenyil-1-picrylhydrazyl (DPPH) radical scavenging activity of meat was determined using the conventional DPPH method as described by Goffman & Bergman (2004). The amount of DPPH was determined at 515 nm, the amount of DPPH was determined at 520 nm, and an ethanolic stock solution (0.4 mL) at each sample of various concentration was added to 1.6 mL of the DPPH solution (80 mg DPPH per liter of 100% ethanol), which was placed at room temperature for 30 minutes. The calculation Formula 2 of DPPH free radical scavenging activity is as follows:

$$\text{DPPH radical scavenging activity}(\%) = (1 - \frac{\text{sample absorbance}}{\text{blank absorbance}}) \times 100 \quad (2)$$

0.5 g of meat sample was added to 2 mL of extract. After homogenizing at 10000 r/min, centrifuge at 8500 r/min for 15 min, and then take the supernatant. The supernatant is a crude extract of •OH radicals. Scavenging activity of the •OH free radical were determined using corresponding diagnostic kits (Nanjing Jiancheng Bioengineering Institute, Nanjing, China) according to instructions.

2.7 Statistical analysis

The data were analyzed using the two-way analysis of variance with a model using SPSS Statistic software 21.0 (IBM Corporation, USA), and means were compared by Fisher's Protected Least Significant Difference (LSD) test in case of significative effect. For all parameters, a probability value of ($P < 0.05$) was considered statistically significant.

The least square multiple linear regression equation in the GLM program of SAS 9.2 was adopted and the biological utilization ratio of organic Se to inorganic Se was calculated with multiple linear regression slope.

3 Results and discussion

3.1 Growth performance of broilers

The effect of Se sources and supplemental levels on growth performance of broilers is presented in Table 2. During the starter (1-21 d), dietary Se sources had no significant effects on FI, BWG and F/G of broilers ($P > 0.05$). With the increase of Se supplemental level, F/G was significantly decreased ($P < 0.05$), and broilers has a significant trend of improvement for BWG ($P = 0.06$). During the finisher (22-42 d), BWG and F/G of broilers were improved with the increase of Se supplemental level ($P < 0.05$), and Se sources and Se levels has a trend of interactions for BWG ($P = 0.07$). During day 1 to day 42, there was a trend of improvement in BWG with different Se sources ($P = 0.08$), and BWG and F/G were significantly affected with increasing percentage of Se supplementation ($P < 0.05$).

When Se was identified as one of the essential trace elements for humans and animals by the World Health Organization in 1973 (Schwarz & Fredga, 1969), Se sources and Se levels have been a hot topic in livestock and poultry farming. Studies have shown that the addition of 0.2 mg/kg sodium selenite and yeast Se to the diet significantly increased BWG and FCR in ruminants (Juniper et al., 2008). Se supplementation also significantly improved feed conversion in poultry (Upton et al., 2009). The results of this experimental showed that the Se sources did not have a significant effect on the production performance of broiler chickens and which were different from previous studies, the reason why the Se sources and Se levels did not have a significant effect on early production performance may be that different forms of Se have different tolerance thresholds (Meng et al., 2019), on the other hand, it may be that the digestive function of chickens is not fully developed and the absorption of trace elements is insufficient, resulting in the growth performance was not obvious, but with the increase of Se supplementation levels, the F/G of broilers was significantly improved at finisher and the BWG of broilers was significantly increased as well. In conclusion, Se levels improved the growth performance of broilers, with the best effect in the 0.6 mg/kg SY group.

Table 2. Effects of Dietary Sodium Selenite and Selenium Yeast Levels on Growth Performance of Broilers.

Time	Item	CG	SS		SY		SEM	*P*-Value		
		0 (mg/kg)	0.3 (mg/kg)	0.6 (mg/kg)	0.3 (mg/kg)	0.6 (mg/kg)		S	L	S × L
Starter (1-21 d)	FI (g)	794.3	783.5	776.2	774.8	780.2	6.34	0.93	0.84	0.80
	BWG(g)	550.1	572.3	580.3	582.8	590.4	6.28	0.88	0.06	0.25
	F/G	1.44	1.37	1.34	1.33	1.32	0.10	0.90	<0.001	0.32
Finisher (22-42 d)	FI (g)	2695.8	2666.7	2680.5	2689.7	2699.4	7.75	0.79	0.85	0.73
	BWG (g)	1324.7	1362.1	1375.9	1375.6	1415.9	7.30	0.20	0.01	0.07
	F/G	2.04	1.96	1.95	1.96	1.91	0.16	0.59	0.02	0.34
All period (1-42 d)	FI (g)	3490.7	3450.2	3456.9	3464.5	3479.6	8.18	0.92	0.88	0.90
	BWG (g)	1874.8	1934.4	1956.2	1958.4	2006.3	7.66	0.08	<0.001	0.28
	F/G	1.86	1.78	1.77	1.77	1.73	0.14	0.79	0.01	0.14

Diets were supplemented with Se from sodium selenite or yeast sources, Sel-Plex® (Alltech Inc., Nicholasville, KY, USA); Se-enriched yeast (SY); sodium selenite (SS); control group (CG); SEM: standard error of mean; Selenium (S), Levels (L) and interaction between Selenium sources and Levels (S × L) effects of dietary Se addition were studied by polynomial contrasts; Means with different lowercase letters differ significantly ($p < 0.05$); FI: Feed intake; BWG: Body weight gain; F/G: feed gain ratio.

Table 3. Mean Scores for Color, Shear Force, pH, Cooking Loss, Texture, and Selenium Content of Chicken Meat Stored at 4 °C.

Item	CG	SS		SY		SEM	*P*-Value		
	0 mg/kg	0.3 mg/kg	0.6 mg/kg	0.3 mg/kg	0.6 mg/kg		S	L	S×L
pH_0	6.28^{b}	6.34^{ab}	6.39^{ab}	6.38^{ab}	6.42^{a}	0.02	0.04	0.05	0.04
pH_{24}	5.60	5.61	5.63	5.63	5.64^{a}	0.02	0.18	0.12	0.55
Shear force	7.16^{a}	6.78^{b}	6.35^{c}	6.45^{c}	6.24^{d}	0.02	0.04	0.03	0.04
L*	57.63	57.65	56.72	56.67	55.81	1.64	0.15	0.09	0.92
a*	10.33	10.07	10.81	10.24	11.09	1.12	0.83	0.03	0.93
b*	10.43	11.72	11.18	10.42	10.97	1.36	0.07	0.19	0.33
Cooking Loss (%)	61.66	60.58	61.00	61.97	61.43	1.62	0.43	0.04	0.28
$Lactate_0$ (mmol/gprot)	0.43^{a}	0.31^{b}	0.27^{cd}	0.28^{c}	0.26^{d}	0.01	0.03	<0.01	0.04
Lactate24 (mmol/gprot)	1.67^{a}	1.42^{b}	1.38^{cd}	1.37^{cd}	1.28^{e}	0.01	<0.01	<0.01	<0.01
Hardness (g)	8066.57^{a}	1683.06^{d}	1911.51^{bc}	2103.02^{bc}	2508.94^{bc}	19.48	0.04	<0.01	0.01
Elasticity (g)	0.55	0.55	0.53	0.54	0.54	0.04	0.36	0.43	0.69
Cohesiveness (g)	0.52	0.49	0.44	0.46	0.47	0.03	0.69	0.02	0.32
Adhesion (N)	3684.88	942.44	744.97	971.90	1228.66	13.67	0.10	<0.01	0.19
Mastication (N)	2069.36	521.98	394.72	521.54	659.14	10.24	0.13	<0.01	0.12
Recovery (g)	0.22	0.19	0.17	0.18	0.19	0.10	0.59	<0.01	0.21

Diets were supplemented with Se from sodium selenite and a yeast sources, Sel-Plex® (Alltech Inc., Nicholasville, KY, USA); Se-enriched yeast (SY); sodium selenite (SS); control group (CG); SEM: standard error of mean; Selenium (S), Levels (L) and interaction between Selenium sources and Levels (S×L) effects of dietary Se addition were studied by polynomial contrasts; Means with different lowercase letters (a–e) differ significantly ($p < 0.05$).

3.2 Meat quality

Effect of different Se sources and supplementation levels on meat quality of broiler thigh muscle is shown in Table 3. Neither the Se sources nor the supplementation levels used in this experiment affected the CIE brightness, muscle maturation loss, elasticity, cohesion, adhesion, chewing and recovery of the meat ($P > 0.05$), but the increase in the supplementation levels significantly affected the a*, cohesion, adhesion, chewing and recovery values ($P < 0.05$). There were significant differences between Se sources and Se levels on muscle pH, lactate levels, shear force, and hardness, and the 0.6 mg/kg SY-fed group had higher pH value at 0, 24 h than that of the other groups ($P < 0.05$). Lactic acid (LA) content was influenced by Se sources and Se levels, and while 0.6 mg/kg SY-fed group had the lowest lactic acid content in current study ($P < 0.05$), and the same case for the meat tenderness ($P < 0.05$).

The freshness, texture, and nutritional content of meat are not only important indicators of meat quality, but also important factors that affect consumers' willingness to buy (Liu et al., 2011). Among them, meat color is the most direct sensory evaluation of consumers. The change of meat color is caused by the oxidation of myoglobin in the muscle, therefore, it is important to prevent muscle oxidation to keep the meat color stable. The addition of yeast Se to the diet significantly improved the meat color by increasing the a* value and decreasing the b* value in the breast muscle of Wolf Mountain males (Wang et al., 2009). In this study, there was no relationship between meat color and Se sources, but the increase of Se could significantly improve the a* value of meat. It is mainly because Se effectively reduces the content of oxygen radicals in tissues and which prevents the oxidation of Fe^{2+} to Fe^{3+} (Liang et al., 2019). The pH value of the muscle is also an important indicator of the reaction to the quality of the meat. Muscle undergoes anaerobic enzymatic production of lactic acid after slaughter (Oliveira et al., 2008), therefore, muscle pH was decreasing with time after slaughter and meat quality reduced as well, but Se supplementation in the diet could improve the ability of myocytes to scavenge metabolites

lactic acid and prevent excessive oxidation of polyunsaturated fatty acids to improve meat quality (Jablonska et al., 2016), It was found that Se supplementation slowed the decrease in pH of pork (Calvo et al., 2016a, b; Liang et al., 2019). Moreover, the higher pH of Se-treated meat could be caused by the higher consumption of hydrogen peroxide (H_2O_2) catalyzed by antioxidant enzymes (Boiago et al., 2014), and on the other hand, it could be that Se regulates some of the glycolysis and slowing down the synthesis of lactic acid (Zeng & Combs, 2008). It was found in current study that there was a significant interaction between Se sources and Se levels on pH and lactate content, where diet with 0.6 mg/kg of SY not only slowed down the decrease of pH but also regulated the synthesis of lactate, both of which are consistent with the above scholars' conclusions. With the improvement of living standard in recent years, the tenderness of meat has become a decisive factor when people choose meat, in the present experimental results, there was a significant interaction between Se sources and Se levels on meat shear. With the increase of Se levels, the cooking loss of meat was significantly reduced and there was no regular change in other textural indicators. The results of this study are consistent with most scholars' findings (Baowei et al., 2011; Calvo et al., 2017; Khan et al., 2018; Li et al., 2018), but some scholars also reported that different levels of Se fermentation products provided no changes in color, water-holding capacity, cooking loss, or shear force (Aristides et al., 2018). The different effects of Se on meat tenderness may be due to the different animal breeds, and no mechanism of Se affect physical properties of meat has been reported at this time.

3.3 Analysis of anti-oxidation ability and lipid oxidation

Effect of different Se sources and Se levels on muscle antioxidant capacity and degree of lipid oxidation is shown in Table 4. Se supplementation in diets increased DPPH (0-24 h), hydroxyl radical (0-24 h) scavenging and increased SOD ($P < 0.05$), and significantly decreased TBARS (0-24 h) and POV values (0-24 h) compared to CG group, except for hydroxyl radical (0 h) for which there was no significant interaction ($P > 0.05$), except for the hydroxyl radical (0 h), which had a significant interaction in all groups ($P < 0.05$). In the present study, it was concluded that the diet with 0.6 mg/kg had higher DPPH (0-24 h), hydroxyl radical (0-24 h) scavenging and SOD values and significantly reduced TBARS (0-24 h) and POV values (0-24 h) compared to all other groups.

There are many antioxidant defense systems in the animal body, including enzymatic and non-enzymatic antioxidant systems, which can scavenge the reactive oxygen radicals (ROS) generated in the body in a timely manner and ensure that the collective free radicals always maintain a dynamic balance to maintain the healthy state of the body (Chung et al., 2006; Chadio et al., 2015; Xu et al., 2018) . Se is widely used in livestock and poultry production as an antioxidant feed additive. Li et al. found that the addition of yeast Se and sodium selenite in broiler diets could improve the enzymatic activity of antioxidant enzymes in the organism compared with the control group (Li et al., 2018), and Traş et al. (2000) found that the addition of Se in the diet could significantly increase the serum SOD activity of broiler chickens, and also prevent and slow down the damage of oxidative effects on the organism. In this experiment, three antioxidant indicators were selected, and the test results showed that the Se sources and Se levels significantly increased the scavenging rate of DPPH and OH radicals and SOD enzyme activity in muscle compared with the control group, with the best effect in the 0.6 mg/kg SY group, which was consistent with the above scholars' findings. The increase in antioxidant capacity of muscle slows down the process of lipid oxidation, thus allowing the meat to obtain a longer shelf life. Ebeid et al. (2013) found that Se supplementation significantly reduced MDA content during 6 days of refrigerated storage. The MDA content of chicken meat was increased with the aging time (Ma et al., 2019). To make the experimental data more convincing, TBARS values (0, 24 h) and POV values (0, 24 h) in muscle were measured in this experiment to assess the extent of muscle oxidation. The results showed that the TBARS (0, 24 h) and POV (0, 24 h) values in the SY group were significantly lower than those in the SS and CG groups, and the lowest levels was found in the SY-fed group at 0.6 mg/kg. By assessing the antioxidant capacity of muscle and the degree of lipid oxidation, we found that the effect of organic Se was significantly better than inorganic Se, and the reason for

Table 4. DPPH and •OH Radical Scavenging Activity, SOD Activities, TBARS and POV Values in Raw Meat Stored at 4 °C (%).

	CG	SS		SY		SEM	*P*-Value		
	0 mg/kg	0.3 mg/kg	0.6 mg/kg	0.3 mg/kg	0.6 mg/kg		S	L	S × L
$DPPH_0$(%)	64.39^{e}	65.50^{d}	66.30^{c}	68.27^{b}	69.50^{a}	0.99	<0.01	<0.01	<0.01
$DPPH_{24}$(%)	67.17^{c}	67.83^{c}	68.60^{b}	68.77^{b}	71.63^{a}	1.18	0.01	<0.01	<0.01
$•OH_0$(%)	100.13	104.40	105.67	107.33	107.73	1.43	<0.01	<0.01	0.11
$•OH_{24}$(%)	100.00^{d}	106.30^{c}	107.23^{bc}	108.33^{b}	110.33^{a}	1.87	<0.01	<0.01	0.03
SOD_0(U/g)	126.13^{e}	133.00^{d}	140.53^{c}	153.63^{b}	163.32^{a}	1.92	<0.01	<0.01	<0.01
SOD_{24}(U/g)	111.43^{e}	115.43^{d}	126.70^{c}	134.67^{b}	144.76^{a}	1.62	<0.01	<0.01	<0.01
$TBARS_0$(mgMDA/kg)	0.47^{a}	0.34^{b}	0.30^{c}	0.28^{c}	0.22^{d}	0.07	0.04	<0.01	0.03
$TBARS_{24}$(mgMDA/kg)	0.77^{a}	0.59^{b}	0.51^{c}	0.40^{d}	0.32^{e}	0.10	0.01	<0.01	0.01
POV_0(meq/kg)	0.56^{a}	0.48^{b}	0.42^{c}	0.36^{d}	0.29^{e}	0.11	<0.01	<0.01	0.04
POV_{24}(meq/kg)	1.76^{a}	1.57^{b}	1.50^{c}	1.36^{d}	1.24 ± 0.01^{e}	0.23	<0.01	<0.01	<0.01

Diets were supplemented with Se from sodium selenite and a yeast sources, Sel-Plex® (Alltech Inc., Nicholasville, KY, USA); Se-enriched yeast (SY); sodium selenite (SS); control group (CG); SEM: standard error of mean; Selenium (S), Levels (L) and interaction between Selenium sources and Levels (S×L) effects of dietary Se addition were studied by polynomial contrasts; Means with different lowercase letters (a–e) differ significantly ($p < 0.05$).

this result may be that the delivery mechanism of organic Se and inorganic Se differ significantly, and organic Se had higher absorption and utilization, bio-safety and enhancement of antioxidant capacity of organisms than inorganic Se. The rate of lipid oxidation in muscle depends on the antioxidant capacity of the animal organism. To make the experimental data more convincing, TBARS values (0, 24 h) and POV values (0, 24 h) in muscle were measured in this experiment to assess the extent of muscle oxidation. The results showed that the TBARS (0, 24 h) and POV (0, 24 h) values in the SY group were significantly lower than those in the SS and CG groups, and the lowest levels was found in the SY-fed group at 0.6 mg/kg, and the test results were consistent with the previous study. By assessing the antioxidant capacity of muscle and the degree of lipid oxidation, we found that the reason for organic Se was better than inorganic Se may be that the delivery mechanism of organic Se and inorganic Se differ significantly, and organic Se has higher absorption and utilization, biosafety and enhancement of antioxidant capacity of organisms than inorganic Se (Wang et al., 2020). The study by Ma et al. showed that organic Se was actively absorbed in the intestine, whereas inorganic Se requires passive absorption (Ma et al., 2014). The analysis by Surai et al. showed that organic Se is more effective than inorganic Se in regulating the antioxidant system of poultry (Surai, 2014). In short, the SY-fed group had greater antioxidant capacity and was more environmentally friendly than the SS-fed group. Feeding 0.6 mg/kg of Se yeast could effectively improve the antioxidant capacity of meat, delaying lipid oxidation and extending its shelf life.

3.4 Selenium enrichment levels in muscle and organs

The result of accumulation of different Se sources and Se levels in muscle and organs is shown in Table 5. Different Se sources increased Se deposition in broiler heart ($P < 0.05$), and which increasing Se levels in the diet improved Se levels in broiler heart, liver, kidney and muscle as well ($P < 0.05$). There were significant differences between Se sources and Se levels on Se deposition on the kidney and heart of broilers ($P < 0.05$). The group with 0.6 mg/kg yeast Se had the highest Se content in muscle and organs. With Se content of heart, liver, kidney and muscle in broilers as indicators, the biological utilization rates of organic Se against inorganic Se were 116.0%, 123.1%, 109.7%, 109.8%, and 135.2%, respectively (Table 6).

Our results showed that the proportion of Se deposition in muscle and liver tissue was increased as Se level in the diet, and the deposition of the two Se sources in the muscle tissue was not significantly different. The organic Se or inorganic Se supplementation in the diet could increase the content of Se in muscle (Marounek et al., 2009). Grossi et al.confirmed this finding, and the study found that muscle Se concentration was improved with the increase in Se concentration in the feed (Grossi et al.,, 2017), and the same results were obtained in studies on beef and lamb (Juniper et al., 2008; Bezerra et al., 2020). In this experiment, there was a significant difference in organic Se and inorganic Se in the deposition of the heart of the chicken. This phenomenon may be caused by the accumulation of organic Se. These discoveries confirmed the high biological effects of organic Se used for chickens (Briens et al., 2014). The increase of Se levels in liver and kidney may be because the activation of Se is in the liver and excreted in the kidneys (Burk & Hill, 2015), and the anti-oxidation constantly repeats this process leading to the deposition of Se in the organs. In word, the enrichment of Se in organs contributes to a timely response to oxidative damage in the organism, and organic Se is more bioavailable than inorganic Se.

4 Conclusions

In conclusion, in the entire breeding process of chickens, with 0.6 mg/kg SY can improve the tenderness and color of the meat, reduce lipid peroxidation, better free radical removal ability and improve Se content in muscle and organs deposition. These results also prove that SY is an effective strategy to improve the quality parameters and antioxidant capabilities of meat in a short period of time, and produce Se-rich meat.

Table 5. Selenium enrichment content in muscle and organs.

Item	CG	SS		SY		SEM	*P*-Value		
	0 mg/kg	0.3 mg/kg	0.6 mg/kg	0.3 mg/kg	0.6 mg/kg		S	L	S × L
Heart (μg/g)	0.07 ± 0.02^{b}	0.08 ± 0.05^{b}	0.18 ± 0.02^{ab}	0.10 ± 0.01^{b}	0.23 ± 0.03^{a}	0.33	0.03	<0.01	0.04
Liver (μg/g)	0.18 ± 0.05	0.27 ± 0.02	0.35 ± 0.01	0.30 ± 0.05	0.43 ± 0.02	0.42	0.15	<0.01	0.21
Kidney (μg/g)	0.17 ± 0.07^{d}	0.34 ± 0.01^{c}	0.44 ± 0.03^{bc}	0.30 ± 0.01^{cd}	0.48 ± 0.02^{a}	0.46	0.39	<0.01	0.04
Muscle (μg/g)	0.08 ± 0.02	0.12 ± 0.02	0.16 ± 0.01	0.10 ± 0.02	0.22 ± 0.02	0.30	0.12	<0.01	0.21

Diets were supplemented with Se from sodium selenite and a yeast sources, Sel-Plex® (Alltech Inc., Nicholasville, KY, USA); Se-enriched yeast (SY); sodium selenite (SS); control group (CG); SEM: standard error of mean; Selenium (S), Levels (L) and interaction between Selenium sources and Levels (S × L) effects of dietary Se addition were studied by polynomial contrasts;

Table 6. Multivariate linear regression equation between inorganic and organic Se.

Parameter	Multiple linear regression equation	Relative bioavailability of organic Se	*P* Value	R^2
Se content at heart	Y = 0.05 + 0.39X(s) + 0.48X(t)	123.1	0.041	0.92
Se content at liver	Y = 0.95 + 0.72X(s) + 0.79X(t)	109.7	0.042	0.98
Se content at kidney	Y = 0.192 + 0.82X(s) + 0.89X(t)	109.8	0.030	0.99
Se content at muscle	Y = 0.09 + 0.23X(s) + 0.31X(t)	135.2	0.001	0.96

Y: (weight of broilers, tissue, and organ Se content and Se Levels), X(s): inorganic Se, X(t): organic Se.

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